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NEW ELECTRONIC TUBES EMPLOYED AS SWITCHES IN COMMUNICATION ENGINEERING

I. CONTACT TUBES

by J. L. H. JONKER and Z. van GELDER. 621.385.832:621.318.57:621.39

The development of telephone exchanges has followed a logical course from manually operated to semi-automatic and thence to the present-day fully automatic exchanges, where subscriber connections are made via mechanical switches operated by electromagnets.

The next phase in the development will probably be the replacement of these electromagnetic relays, selectors, etc. by electronic tubes. One of the advantages of the latter, compared with mechanical switches, is that they have much less inertia, so that they can perform their functions more quickly and thus return earlier to their state of rest ready for the next duty. This means a saving in switching material.

Although the development of special electronic tubes for replacing relays and the like has scarcely begun, laboratory work has already led to the development, in a technically useful form, of a number of types, about which something will be said in this and a following article.

Apart from automatic telephony, these "contact tubes" will also find application in other fields where switching has to be done quickly — either synchronously or not — as is the case in certain systems for multiplex connections, for code modulation, for colour television, etc.

For making and breaking connections in line telephony wide use is made of switches in the form of electromagnetic relays. The simplest types are represented in *fig. 1.* The contacts of relays are subject to corrosion and therefore need cleaning regularly. Another important factor with these relays is the switching speed. This is limited by the inertia in the appearance and disappearance of the magnetic field, or by the inertia of moving parts.

It can be understood that in the search for switches not requiring any attention and having less inertia thought should begiven to electronic tubes, whose switching speed may be 10^2 to 10^4 times higher. Conventional amplifying valves in which the intensity of a stream of electrons is controlled by one or more grids are sometimes used as relays in telephony in certain cases, but there is no question of these valves — designed for quite different purposes — being able to perform the function of, for instance, a relay with make-and-break contacts. Even if the very simplest relay (fig. 1*a*) used in telephony were to be considered for replacement by a normal radio valve there would be the difficulty that the anode alternating voltage is in antiphase with the grid voltage. When transmitting pulses these would arrive either with one polarity or with

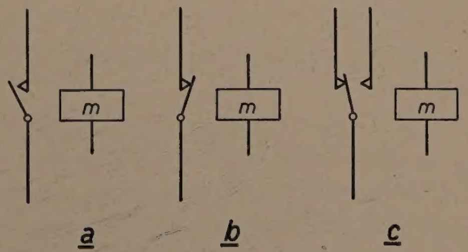

Fig. 1. *a*) Relay with a make contact, *b*) relay with a break contact, both drawn in the position where the magnetic coil *m* is not excited. *c*) Relay with a switch contact (two-way switch; the other two relays are single-way switches).

the other, according to whether the varying number of stages in the connection is even or odd. Only with rather complicated measures might it be possible to overcome this difficulty. Such measures, however, are not needed when an electronic switch is available which, just as is the case with an ordinary switch, would produce no phase difference between the input and output voltages. Presently it will be seen that such a manner of making electronic contact is possible by employing secondary emission, which is in fact done in all the tubes that are to be dealt with in these articles ¹).

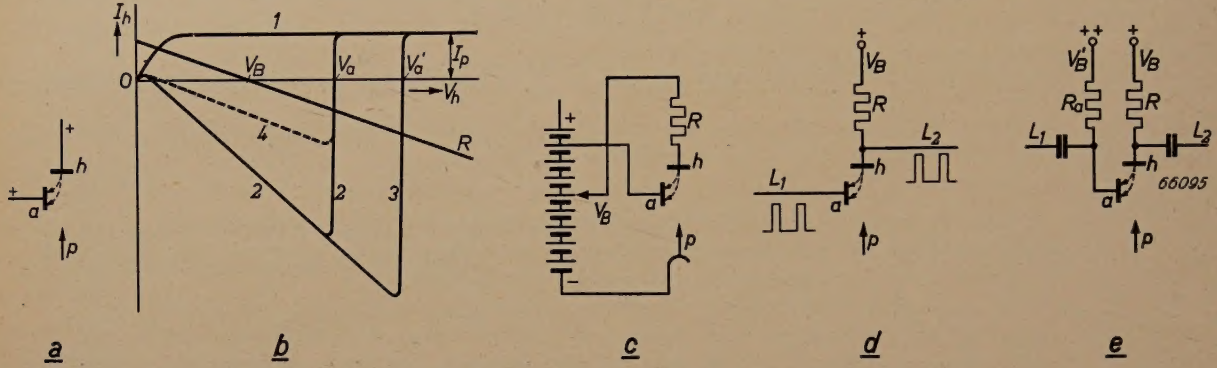

Fig. 2. *a*) A stream of primary electrons *p* is directed onto an electrode *h*, from which secondary electrons are released which proceed towards a collecting electrode *a* at a positive potential.
b) The current I_h from the electrode *h* as a function of the voltage V_h at the same electrode, *1*: for the case where *h* is not emitting secondary electrons, *2*: with secondary emission from *h* and a voltage V_a on the electrode *a*, *3*: the same as *2* but with a higher voltage (V_a') on the electrode *a*, *4*: the same as *2* but with weaker secondary emission.
c) The electrode *h* is connected across a resistor *R* to a point of positive potential V_B, so that the point of intersection of the line *R* on one of the characteristics — see (*b*) — becomes the working point.
d) The collecting electrode *a* functions as input electrode and *h* as output electrode. Positive pulses on the telephone line L_1 are transmitted to the line L_2 as long as the primary electron current reaches *h*.
e) Circuit for transmitting an arbitrary alternating voltage from line L_1 to line L_2. The input electrode *a* receives a positive bias via the resistor R_a.

These tubes, it is to be emphasized, are to be regarded as still being in the experimental stage. Nevertheless in their shape and dimensions (they are of about the same size as a normal radio valve) and, of course, in their electrical properties — to be discussed later — they show that account is being taken of practical requirements right from the outset.

According to the manner in which the stream of electrons emitted by the heated cathode is directed to or diverted away from a certain spot in the tube (corresponding to the closed or open position of a certain contact), the types of tubes to be dealt with here can be divided into two groups:

1) those where the stream of electrons is passed or blocked by a control grid — these are contact tubes, corresponding to relays with one or more make contacts — and
2) those where an electron beam is deflected (as in a cathode-ray tube) — these are commutator tubes, corresponding to relays with one or more make and break contacts or to multi-way switches.

In this article we shall deal only with tubes of the first group, but first it will be useful to discuss the principle underlying electronic contact-making with the aid of secondary emission.

Contact-making with the aid of secondary emission

The principle of effecting an electronic contact with the aid of secondary emission ²) is illustrated in *fig. 2*. A stream of primary electrons *p* is directed towards an electrode *h* (fig. 2*a*) at a positive potential V_h. Assuming that this electrode is incapable of emitting secondary electrons, then the current I_h in the supply lead of the electrode *h*, which depends on the voltage V_h, follows the curve

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¹) These tubes have partly also been dealt with by J. L. H. Jonker in "Valves with a ribbon-shaped electron beam: contact valve; switch valve; selector valve; counting valve", Philips Research Reports 5, 6-22, 1950 (No. 1).

²) It has already been incidentally described in this Journal (Philips Techn. Rev. 11, 141, 1949, fig. 12) as being used in a circuit called an "anode follower".

1 in fig. 2*b*; I_h soon reaches a saturation value given by the intensity I_p of the stream of primary electrons. If, on the other hand, the electrode *h* has been processed in such a way as to be able to give a high secondary emission, and in the valve there is an electrode *a* (fig. 2*a*) at a certain positive potential V_a, then at low positive values of V_h secondary electrons will be emitted and these will proceed towards the electrode *a* having a higher potential. As soon as the number of secondary electrons released per second from *h* exceeds the number of primary electrons impinging upon *h*, I_h becomes negative (see the descending part of the curve *2* in fig. 2*b*, the so-called dynatron characteristic). When V_h is made approximately equal to V_a the secondary electrons can no longer be taken up by *a*. They then return to *h*, so that in this range ($V_h \approx V_a$), I_h rapidly increases until the curve *1* is again reached. If V_a is given a higher value (V_a') a characteristic is obtained like that of curve *3*.

When the electrode *h* is connected via a resistor *R* to a direct-voltage source V_B (fig. 2*c*), then V_h is as represented by the straight line *R* (fig. 2*b*) as a function of the current I_h through *R*. The point where this line *R* intersects the curve *2* indicates the values of the current and voltage at the electrode *h* when the voltage at the other electrode *a* is V_a. If the values of *R* and V_B are chosen such that the point of intercection lies on the steep part of the curve *2* — as represented in fig. 2*b* — then the potential V_h corresponding to this point is practically equal to that corresponding to the point where the curve *2* intersects the abscissa, thus about V_a. Imagining V_a to be variable, then V_h follows the variations of V_a, without changing polarity. In other words, there is, as it were, contact between the electrodes *h* and *a*, which we may call the output electrode and the input electrode respectively.

When, for instance, a telephone line L_1 (fig. 2*d*) carrying positive pulses is connected to the electrode *a* and another line L_2 is connected to *h*, the pulses are transmitted from L_1 to L_2 as long as primary electrons are impinging upon *h*. For the transmission of an arbitrary alternating voltage (for instance with audio frequencies) we proceed as indicated in fig. 2*e*; here the potential of *a* consists of a constant bias, derived via a resistor R_a from a direct-voltage source V_B, and of the alternating voltage derived, say, from the line L_1 connected to *a* across a blocking capacitor, in the same way as L_2 is connected to *h*. As long as primary electrons are impinging upon *h* the voltage at *h* follows that at *a* and thus L_2 has the same alternating voltage as L_1. To break the contact in the cases of figures 2*d* and 2*e* it suffices to apply to a control grid in the vicinity of the cathode a negative voltage which is sufficient to suppress the primary stream of electrons.

The "voltage drop" in the contact, $V_a - V_h$, is small and depends only slightly on the magnitude of the secondary emission, provided it has been arranged that the line *R* intersects the characteristic approximately in the middle of the steep part: practically the same point of intersection is then found for an electrode *h* with weaker secondary emission (curve *4* in fig. 2*b*).

The contact described with reference to fig. 2*d* is unilateral, since unless other measures are taken V_a does not follow any fluctuations of V_h. In communication engineering use is very often made of separate channels for the outgoing and the return connections. For such a unidirectional channel a unilateral contact therefore suffices, and this condition is satisfied in most of the tubes to be discussed in this article. For those cases, however, where a bilateral contact is necessary another tube has been developed as described in the next section.

With the circuit of fig. 2*e* a bilateral contact is nevertheless possible within certain limits. If, for instance, V_h is increased by a voltage from L_2 then equilibrium is not restored until V_a is increased by the same amount: if V_a were to lag behind the rising V_h then secondary electrons could no longer pass from *h* to *a* and the current through R_a would decrease, which means that V_a does after all increase. The same argument can be followed to show that V_a will decrease as V_h drops.

V_a is not, however, unrestricted in following the fluctuations of V_h. In the first place V_a cannot follow V_h when the latter exceeds the value V_B', because this is the highest potential that *a* can reach (that is why it is favourable to choose a high value for V_B', higher than V_B). As V_h decreases another limit is reached on account of the secondary emission diminishing with the decrease of V_h until *h* is no longer capable of supplying the larger current through R_a that would be needed for the same decrease of V_a.

If a contact tube with bilateral action is needed then a tube working on the principle described may serve, but, generally speaking, a tube of the kind described below, which has been designed for bilateral action, will be more suitable.

Symmetrical contact tube

A bilateral contact, identical in both directions, is obtained when the device of fig. 2*e* is made entirely symmetrical. To achieve this both the electrodes *h* and *a* (denoted in *fig. 3* by h_1 and h_2) are processed for high secondary emission. They are placed symmetrically with respect to the primary stream of electrons and both are connected via a resistor R to a point of positive potential. This tube operates as follows.

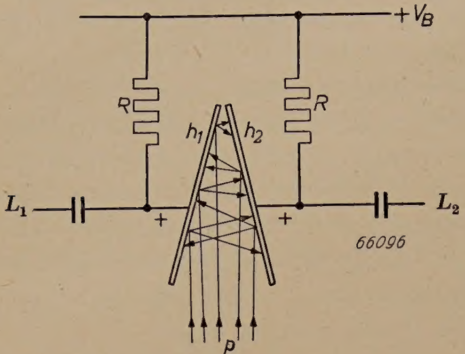

Fig. 3. Entirely symmetrical, bilateral, electronic contact. The primary electrons p impinge upon two symmetrically placed electrodes (h_1 and h_2), both with secondary emission properties and each connected across a resistor R to a point of positive potential V_B. L_1-L_2 external circuit.

We shall first consider only the secondary electrons emitted by the electrode h_1; the potentials of h_1 and h_2 will be denoted by V_1 and V_2 respectively. As long as V_2 is greater than V_1 all these electrons will be attracted towards the electrode h_2. This corresponds to the horizontal part of the curve *1* in *fig. 4*. When the potential difference is reversed ($V_2 < V_1$) then the secondary electrons leaving h_1 may travel more or less in a direction opposed to the electrical field, as their initial velocity is much higher than that of the electrons leaving a heated cathode (see the curved left-hand part of the characteristic *1*). A similar characteristic applies for the secondary electrons emitted by the electrode h_2 (curve *2* in fig. 4). The current flowing in the external circuit (L_1-L_2 in fig. 3) is found by adding the ordinates of the curves *1* and *2*. This gives the curve *3*, which is the current-voltage characteristic of the electronic contact. The corresponding characteristic of an ideal contact would be the I-axis, that of a contact with a low resistance the dotted line *4*. The characteristic *3* closely approximates *4*, being practically linear round about the origin, so that the contact can transmit in both directions, for instance, alternating voltages at audio frequencies without any appreciable distortion. The angle between the tangent to *3* at the origin and the I-axis is a measure of the resistance of the contact, which is inversely proportional to the intensity I_p of the primary stream of electrons. With $I_p = 1$ to 2 mA a contact resistance in the order of 1000 ohms can be reached.

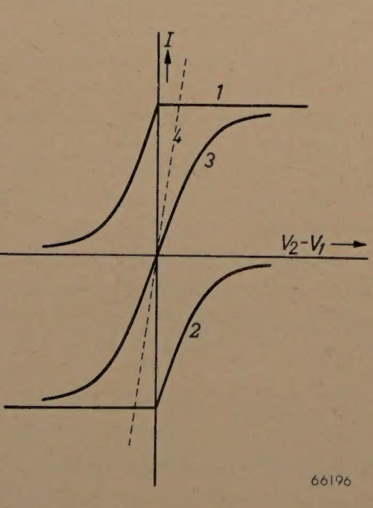

Fig. 4. Plotted as functions of the potential difference V_2—V_1 for the tube of fig. 3: *1* the current strength of the secondary electrons from h_1, *2* that of those from h_2, *3* the total current found by adding the ordinates of *1* and *2*. For comparison the dotted line *4* gives the current-voltage characteristic of a normal contact of low resistance.

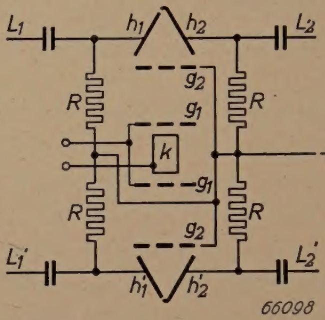

Fig. 5. Bilateral contact tube according to the principle of fig. 3, in double-pole execution. k is the common cathode, g_1 the control grid, g_2 an auxiliary grid at a positive potential, h_1-h_2 and h_1'-h_2' the secondary emission electrodes to which are connected, for example, the lines L_1-L_2 and L_1'-L_2'.

The electrodes h_2 and h_2' are slightly lengthened and bent over in order to prevent electrons reaching the bulb and there causing undesired secondary emission.

The symmetrical contact tube described can be improved in some respects simply by applying a grid g_2 (see *fig. 5*, representing a bipolar contact tube) of such dimensions and at such a positive potential that a part of the secondary emission from the electrodes h_1 and h_2, respectively h_1' and h_2', is drawn away which just corresponds to the current of the primary stream of electrons. The current then flowing through the resistors R is very small. This means that the average potential of the electrodes h is raised (almost equal to V_B), so that the secondary emission coefficient is greater and the current to be transmitted may be greater. When the primary electron stream is switched off the potential of h rises only to the slightly higher value V_B; thus when the contact is closed or opened (passing or suppressing the electron stream respectively) only insignificant voltage pulses arise in the circuits connected to the electrodes h. The advantages mentioned are still obtained if the resistances are chosen so high as to form only a small load for the circuits.

Fig. 6 is a photograph of the tube last described.

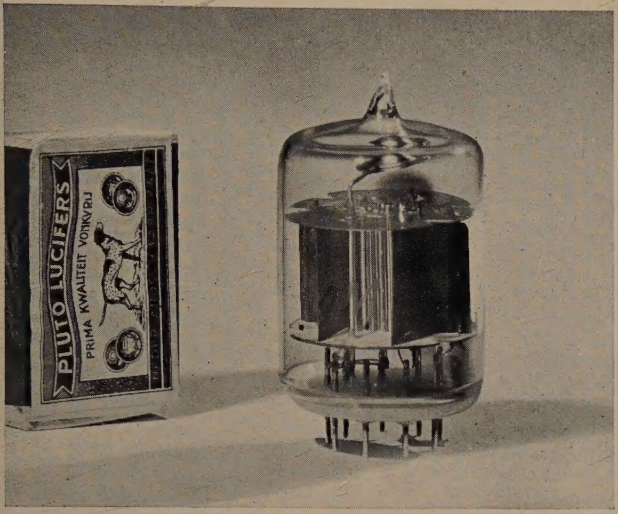

Fig. 6. Photograph of the tube schematically represented in fig. 5.

Limited switching possibilities with tubes of the type discussed

In telephony there are many cases where the requirements demanded of the relays cannot be met, or only partly, with the type of tube described above. It is often desired to connect a fairly large number of relay contacts in series and at least a few of them in parallel. With electromagnetic relays this requirement is easily satisfied. With tubes of the type described, however, this is not so easy when more than three of them are connected in series. This will be briefly explained before discussing the solution that has been found for this problem. In the case of parallel connection, which we shall not go into here, no special difficulties arise.

In *fig. 7* we have a diagram representing the series connection of three contact tubes (for transmission in one direction) as shown in fig. 2. It is presupposed that the resistances R are of such a value that the currents flowing through them are negligible in comparison with the primary electron currents, which are assumed here to be equal in intensity $(I_{p1} = I_{p2} = I_{p3}, = I_p)$. The secondary-emission electrode h_3 of the third tube will then assume such a potential that its secondary emission coefficient, δ_3, is equal to 1. There then flows to the collecting electrode a_3 a stream of secondary electrons, $I_{\text{sec}3}$, equal to I_{p3}. This current reaches the electrode h_2 of the second tube together with the primary current I_{p2}, so that h_2 must emit a secondary electron current equal to $I_{\text{sec}3} + I_{p2} = 2I_p$. Since the intensity of the primary electron current reaching it is only $I_{p2} = I_p$, h_2 must assume a potential at which the secondary emission coefficient δ_2 is equal to at least 2. In the same way it can be deduced that the electrode h_1 of the first tube will assume a potential at which its secondary emission coefficient δ_1 is equal to at least 3 and, with n tubes connected in series, equal to n. Now for a substance with good secondary emission like caesium, with a primary electron energy of 200 eV the secondary emission coefficient is at most about 5. Taking into account the finite value of R, the δ's must be even slightly greater than n, for the currents through these resistors must also be compensated. Thus the number of electronic contacts that can be connected in series is limited in practice to only three.

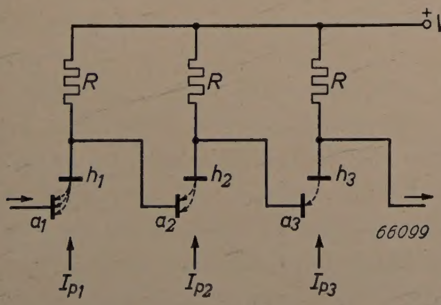

Fig. 7. Three unilateral electronic contacts according to fig. 2*d* connected in series.

It is, however, possible for many more contacts to be connected in series if the two functions hitherto performed by the electrode a, namely the function of input electrode and that of collecting electrode, are separated. The contact system then consists of three electrodes, with the input electrode in the form of a grid to which hardly any current flows.

Contact system with input electrode in the form of a grid

Fig. 8 is a schematic representation of a unilateral contact system with three electrodes, where the primary electrons impinge upon an electrode h with secondary emission and forming one of the contact electrodes (the output electrode); the input electrode in the form of a grid is now denoted by r. By far the majority of the secondary electrons coming from h pass through the meshes of the grid and reach a third, collecting electrode a at a fixed and higher potential. As is the case in fig. 2, h follows the potential variations of r (in this case it is more correct to say that it follows the potential variations in the plane of r). The small current flowing to r can be compensated for the greater part by arranging for this electrode to emit per second about just as many secondary electrons as there are primary electrons impinging upon it ($\delta \approx 1$); such is the case if the surface of the metal is not contaminated.

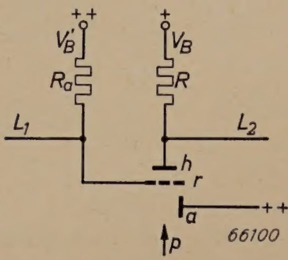

Fig. 8. Contact system with input electrode in the form of a grid. *p* primary electrons, *h* secondary-emission output electrode, *r* input electrode in the form of a grid, *a* collecting electrode at a fixed, high potential. L_1 incoming line, L_2 outgoing line.

When a number of these contacts are connected in series there is much less trouble from the difficulty discussed above, as practically no current flows towards the electrodes *r*. About ten contacts can then quite well be connected in series, a number which is ample for very many practical cases.

The voltage difference across the closed contact can be made very small (even negative) owing to the fact that the electrode *a* at high potential can be made to bring about in the plane of the grid *r* a potential which is higher than that of the grid itself.

This contact system with three electrodes has been applied in tubes in which the primary stream of electrons is guided in the desired direction by electrostatic deflection. Further particulars of this will be given in another article to follow.

Summary. This is the first of two articles in which some experimental tubes are described which are intended to function as switches. These contact tubes have the advantage over electromagnetic relays in that the switching speed is much greater and no cleaning of the contacts is required.

Contrary to the case of ordinary electronic valves, where the output signal is in antiphase with the input signal, these new tubes are characterized by the two signals being in phase, thereby avoiding many complications. This property is due to a secondary-emission output electrode being employed which follows the potential of the input electrode. The "contact" thus existing, as it were, between these electrodes can be broken by suppressing the primary beam of electrons with the aid of a control grid. The contact is unilateral, the output electrode following the potential variations of the input electrode (with the same phase!, whereas the reverse is not usually the case. In telephony such a unilateral contact often suffices. Nevertheless a symmetrical contact tube, for a bilateral contact, has also been developed. The current-voltage characteristic of the contact is practically linear round about the origin; the contact resistance is in the order of 1000 ohms.

In some cases it is a drawback that no more than three of these contacts can be connected in series, but this can be largely overcome by arranging for the functions of input and collecting electrodes to be performed by two separate electrodes ("contact system with input electrode in the form of a grid"). As many as about ten contacts can then be connected in series.

FLICKER IN TELEVISION PICTURES

by J. HAANTJES and F. W. de VRIJER.

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In a television picture flicker is sometimes experienced. It is therefore important to investigate how flicker can be eliminated. With a suitably chosen luminescent material on the screen of the cathode-ray tube it appears to be possible to reduce flicker considerably, so much so that under normal conditions this effect is entirely absent.

The object of motion-picture projection and television is to reproduce moving scenes as naturally as possible. The fact that this can indeed be technically achieved is due to a fundamental deficiency of the human eye, namely its inability to perceive as separate stimuli a rapid succession of optical impressions. The result is that a series of pictures with only small differences and quickly following one upon the other appear as one continuously changing picture. Of course the separate pictures must follow each other at a sufficiently high frequency. But even when this condition is satisfied an unpleasant effect may arise — the picture flickers. Only when the frequency is raised much higher does this effect disappear.

For film projection the picture frequency has been standardized at 24 pictures per second. The illumination of the film picture is intermittent, being blacked out during the change over from one picture to the next, so that each time a stationary picture appears on the screen. Were it not for the special measures that are taken, at this picture frequency the flicker effect observed would be considerable. The frequency of the projection is therefore raised artificially by interrupting the illumination once more during the projection of each separate picture (the light and the dark intervals are made equal in length). In this way a frequency of 48 pictures per second is reached — two successive pictures are the same — and, as everyone is aware, no trouble is experienced from flicker in a cinema.

For television, too, a series of pictures are made to follow each other in rapid succession, but here the situation is more complicated than in the case of film projection. The picture screen, which is covered with a layer of a fluorescent substance (phosphor), is scanned line for line by a beam of electrons, thereby causing the phosphor to luminesce also line for line. It is desired to keep the frequency at which the "frame" is completely scanned as low as possible, because the bandwidth of the video signal is directly proportional to that frequency. Further, it is advantageous (at least it was felt to be so during the development of television) to match the picture frequency to the mains frequency, and that is why in European countries it is customary to use a picture frequency of 25 c/s, whilst in the U.S.A. it is 30 c/s (in both cases half the mains frequency). Although such frequencies are sufficiently high for reproducing a continuous movement, they are too low to avoid flicker. Consequently interlacing is generally applied, which means that, instead of all the horizontal lines being scanned by the electron beam in the natural sequence, for instance first all the even lines are scanned and then all the odd ones, and so on. Thus twice as many frames are scanned per second, though each has only half the total number of lines, and so frame frequencies are reached of 50 and 60 c/s respectively.

The question now arising is whether such a frequency is high enough to avoid flicker. Owing to the entirely different build-up of the picture the experience gained in motion-picture projection does not suffice to answer this question. Much experimentation has therefore been directed towards the solution of this problem especially for television. In the present article some experiments will be described which have been conducted in the Philips Laboratories at Eindhoven and which were demonstrated in the spring of 1950 on the occasion of a visit to Eindhoven of the 11th committee of the "Comité Consultatif International de Radio" (C.C.I.R.). An extensive report on these experiments has been published elsewhere [1]).

Before proceeding to deal with these experiments it is well to consider briefly those properties of the eye upon which the flicker effect is based.

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[1]) J. Haantjes and F. W. de Vrijer, Flicker in Television Pictures, Wireless Engineer **28**, 40-42, Febr. 1951.

Physiology of flicker

When the eye is suddenly exposed to the light from a light source (a lamp, or an illuminated screen) of constant luminance the signal transmitted by the optic nerve to the brain will be as represented by the curve in *fig. 1.* At the instant, t_1, that the light falls on the eye the observer does not immediately perceive anything, but after a short time (in the order of 0.01 sec) the signal gains in strength and ultimately reaches its maximum after an interval τ_1. Then the stimulus diminishes slightly in intensity but later remains constant. Upon the light source being extinguished at the instant t_2 the signal still remains constant for a short while (again about 0.01 sec) but then diminishes practically exponentially to zero in a period of time τ_2. It may therefore be said that the eye perceives an optical impression with a certain inertia. This inertia is characterized by the intervals τ_1 and τ_2, which are practically equal and from now on will be denoted by the one symbol τ. Experiments teach [2]) that τ depends upon the luminance B of the light source and the colour of the light, whilst also the solid angle under which the light source is seen and the place where the light falls upon the retina are of influence. The value of τ is in the order of 0.1 sec.

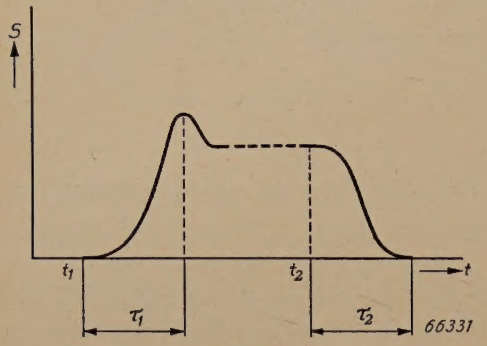

Fig. 1. The signal S, transmitted by the optic nerve to the brain of an observer whose eye at the moment t_1 is suddenly exposed to an impression of light, rises to a maximum value in a finite time τ_1, then falls slightly and after that remains constant. Upon the light source being extinguished at the moment t_2 the strength of the signal gradually diminishes to zero in a period of time τ_2. The intervals τ_1 and τ_2 are in the order of 0.1 to 0.2 sec (for normal luminances); they also depend upon the conditions under which observations are made and, further, differ as between one person and another.

Tests carried out by Hartline [3]), among others, show that in addition to the normal receptors behaving as described above, in the retina there are also other receptors reacting particularly to "on" and "off" stimuli. The latter receptors pass a signal to the brain only when the optical impression begins and when it ends, but not during the exposure. There are even some receptors responding only to extinction of the light. Such receptors are naturally of the utmost importance for the perceptibility of flicker. Not much is yet known on this subject except that these receptors occur mainly on the periphery of the retina. This is one of the explanations for the fact — dealt with farther on — that flicker becomes more noticeable when the light falls upon the edge of the retina.

When flashes of light are caused to strike the eye at such a frequency that the interval between two successive flashes is much shorter than τ then they will be observed as one constant impression of light; the brightness of the flashing light source is then perceived as the average brightness of that source over a full cycle of the alternation (Talbot's law).

Talbot's law can be demonstrated with a simple experiment: in front of a light source, say an incandescent lamp, a disk is set up which can be rotated at a variable speed and from which one or more sectors have been removed, so that the light from the lamp is cast for part of each cycle upon a white screen placed in front of the disk; the screen serves as light source for an observer. Talbot's law appears to apply for frequencies higher than about 15 c/s; hence for these frequencies the observed brightness of the screen does not depend upon the speed of the disk.

When the frequency is round about 15 c/s the law is no longer satisfied: probably owing to a resonance phenomenon, the eye then perceives a greater luminance. At such frequencies (thus in the case where the cycle is in the order of τ; as a matter of fact to some extent also at higher frequencies) there is considerable flicker effect, whilst at still lower frequencies each flash is observed as such separately.

When investigating more closely how flicker depends upon the frequency we find the following.

For a given luminance B of the screen there appears to be a critical frequency f_c above which the eye no longer perceives any flicker. When the frequency of the alternation between light and dark is lower than f_c flicker is perceptible; the lower the frequency (to a certain limit), the more unpleasant is the sensation. The higher the level of the screen luminance, the higher is the critical frequency, there being an almost linear relation between f_c and the logarithm of B;

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[2]) See, e.g., Y. Le Grand, Optique physiologique, Tome II, Editions de la "Revue d'Optique", Paris 1948.

[3]) H. K. Hartline, J. Opt. Soc. Am. **30**, 239, 1940.

$$f_c = a \log B + b. \quad \ldots\ldots \quad \text{(1a)}$$

This is the Ferry-Porter law.

So far we have not considered the luminance of the surroundings, which also has its effect upon the result. It appears, however, that when the luminance of the surroundings is small compared with that of the screen it has practically no influence upon the results of the tests.

When the luminance of the screen is not too low ($B > 0.1$ cd/m^2) the coefficient a lies between 10 and 20 sec^{-1}, so that from formula (1a) it follows that the critical frequency rises 10 to 20 c/s when B is increased by a factor 10.

Flicker is naturally a subjective phenomenon, the results of the tests varying considerably for different persons and under different conditions. When there are influences distracting the observer's attention flicker is generally less noticed. Consequently we can only speak of averaged results.

For television practice, where the frequency is fixed, one may introduce the term critical luminance. If the luminance of the screen (at given a frequency) is less than this critical luminance B_c no flicker is noticed, but if it is greater than B_c then flicker will indeed be noticed. For this case we can write the Ferry-Porter law as:

$$\log B_c = \frac{f-b}{a} \quad \ldots\ldots\ldots \quad \text{(1b)}$$

The lower the frame frequency the smaller is B_c, and hence the frequency sets a limit to the permissible luminance of a television picture.

The coefficients a and b depend upon the manner in which the luminance of the screen varies with time, particularly upon the ratio in length of the light and dark intervals. This can be shown by varying the size of the sector in the rotating disk. This phenomenon is demonstrated in *fig. 2* (constructed from data given by Engstrom [4])). It is seen that with a given frequency the critical luminance increases with the part of the total cycle covered by the light interval, as is understandable considering that then the case of continuous illumination is more closely approached. As far as television is concerned it may therefore be concluded that the finite decay time of the fluorescent screen will have a favourable effect upon flicker.

In motion-picture projection a luminance of about 35 cd/m^2 occurs in the brightest parts of the picture. As explained in the subscript to fig. 2, from the graphs it can be directly determined what frequency will be high enough to avoid flicker in the case of equality between the light and dark intervals of the illumination. It is seen that a frequency of 48 c/s is indeed sufficient.

Also the solid angle under which the screen is observed appears to influence the coefficients a and b. This is intimately related to the fact already mentioned that flicker is more noticeable the more of the light from the screen (or a part thereof) falls upon the periphery of the retina. This may easily be verified with the aid of a gas-discharge lamp (say a "TL" lamp) working on an alternating voltage. When the eye is directed straight onto the lamp the light is not seen to flicker (or scarcely so), but when the eye is turned upon some point in the vicinity of the lamp some flicker is noticed.

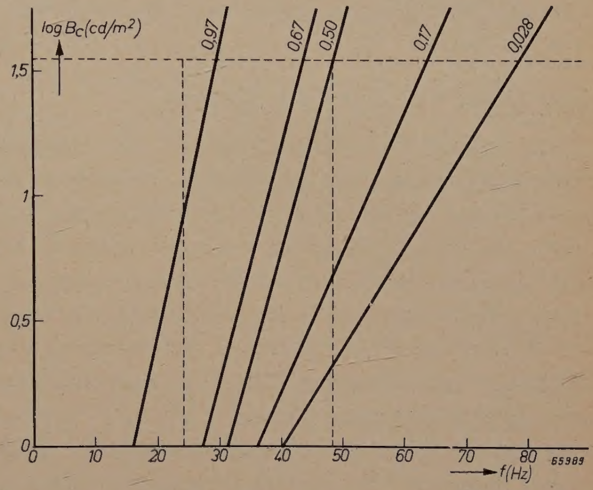

Fig. 2. With a given distance between the observer and an intermittently illuminated screen the logarithm of the luminance at which the observer just perceives flicker (the critical luminance B_c) varies linearly with the frequency f of the optical signal. The coefficients in this Ferry - Porter law depend, inter alia, on the manner in which the light and dark periods alternate, and in particular on the ratio of the lengths of these periods. The various straight lines in the diagram apply for the ratios of light to dark periods indicated. In film projection the intervals are equal and thus the relation between the critical brightness B_c and the frequency is given by the line indicated by the parameter value 0.50. In this case the desired screen luminance (in the lightest parts of the picture) is 35 cd/m^2 (horizontal broken line). With a picture frequency of 24 c/s (projection without additional interruption of the light) this brightness is far above the critical luminance (vertical broken line on the left), but with double that frequency it comes just below B_c (vertical broken line on the right) and thus no flicker is then observed. (Constructed from data given by E. W. Engstrom [4]).)

The colour of the light has very little effect upon the perceptibility of flicker, at least upon the critical frequency. This fact even makes it possible to compare the luminances of differently coloured light sources. By definition it is said that two light sources have equal luminance when they show the same critical frequency.

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[4]) E. W. Engstrom, A study of television image characteristics, Proc. Inst. Radio Eng. **23**, 295-310, 1935.

The fact that flicker is practically independent of colour is made use of also in the flicker photometer, with which the brightness is compared of differently coloured planes viewed in rapid succession. The luminance scale found with the flicker photometer for the various colours (or rather chromaticities) agrees well with the luminance scale defined with the aid of the international luminosity curve ⁵).

This is not the place to enter into a deeper discussion of the subjects touched upon above, and reference is therefore made to the extensive literature available (see, for instance, the publication cited in footnote ²)).

Experiments with television pictures

The experiments which yield us the data for determining, e.g., the minimum frequency for motion-picture projection (as already seen, with the luminance of 35 cd/m^2 a frequency of 48 c/s suffices) have to be extended when we come to consider these phenomena for the case of television. This is because, as intimated in the foregoing, the build-up of the television picture is quite different from that of the film picture.

Furthermore, in the case of television a much greater luminance is required, since it is desired to be able to view the picture in surroundings which are not blacked out or only slightly dimmed. This makes it necessary for the luminance to be more than one hundred cd/m^2. The fact that it is nevertheless possible to reach satisfactory results with a frame frequency of 50 c/s is due to the finite decay time of the fluorescent substance used for the screen.

As already described several times in this journal ⁶), the intensity of the light emitted by the phosphor does not disappear immediately after the electron beam has passed, but rather decreases almost exponentially with time. If the decay time is long (say 5 times longer) compared with the time it takes for the electron beam to scan one line, then at any moment several picture lines will be luminescent. Such a band of light has not the same intensity everywhere: as the beam scans the screen in horizontal lines from top to bottom the uppermost lines of the band will be less luminescent than the lowermost ones. If the decay time of the phosphor is of the same order as the "line time" then the "band" has a width of only one line, and there will even be a difference in luminance in the horizontal direction. In practice phosphors are used with a decay time between some hundreds of times the line time and about one line line time. The situation is made still more complicated by the fact that often a mixture of two (or more) phosphors has to be used to give a screen a white luminescence. One of the components may give, e.g., blue light and have a short decay time, while the other component gives yellow light and has a long decay time.

It has been seen that a phosphor with a long decay time is favourable as regards flicker: the decay time of the phosphor in the case of television takes the place, as it were, of the ratio in the lengths of the light and dark intervals in film projection. Some experiments have been carried out to investigate this effect of the phosphor. At the same time the dependency of flicker upon the distance between the observer and the screen was determined, thus its dependency upon the solid angle from which the screen is seen, and also its dependency upon the picture frequency. Tests were carried out with ten observers in a room where the luminance of the surroundings was low compared with that of the picture; in this case the ambient luminance has little effect upon the results. Each observer was allowed a few minutes for visual adaptation before the test began. Only the average of their observations is given here. The maximum spreading between the critical luminances observed amounts to a factor 4; none of the observers gave a luminance below 70% of the average, whilst only in one exceptional case was the critical luminance given three times higher than the average (by an observer who was apparently very insensitive to flicker).

It is to be noted that all the tests described here were carried out with a fixed number of lines, viz. 625.

A study was made of the relationship between the distance from the observer to the screen and the critical luminance as perceived by the observer when using different mixtures of phosphors, at a frame frequency of 50 c/s. The luminance was defined as an average in time (Talbot's law), but not as an average in position. The latter is of no consequence when taking measurements with a television screen on which only the frame is scanned, thus without a picture, but it does count

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⁵) See R. W. Pohl, Einführung in die Physik, Band III, Optik; Berlin, Springer-Verlag, 1943.

⁶) See, e.g., F. A. Kröger and W. de Groot, The influence of temperature on the fluorescence of solids, Philips Techn. Rev. **12**, 6-14, 1950 (No. 1). There the decay time of a phosphor is defined as the time in which after interruption of the excitation the luminous intensity drops to 1/e of its original value.

when measurements are taken with a normal television picture. In the latter case a distinction has to be made between the average luminance and the high-light luminance (in the white parts) of the picture. In *fig. 3* curves are given showing the relation between this high-light luminance and the viewing distance, it being borne in mind that the average luminance of the picture may be a factor 5 lower. In point of fact a distinction should also be made between stationary and moving pictures. In the latter case less flicker is noticed, probably owing to the observer's attention being distracted.

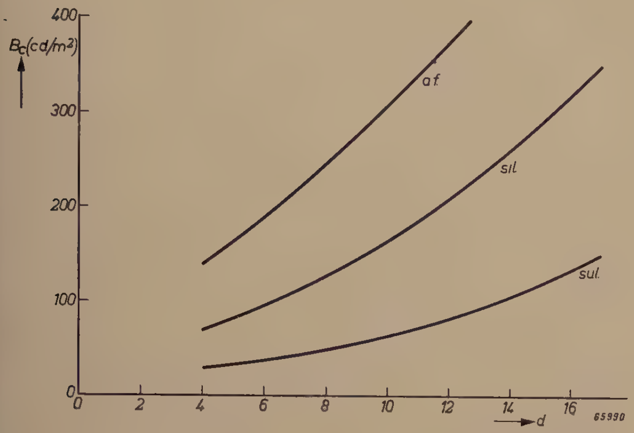

Fig. 3. Critical high-light luminance B_c of a television picture as a function of the viewing distance d (expressed with the screen height as unit). The three curves relate to the three luminescent mixtures mentioned in the text. The frame frequency is 50 c/s.

As the graphs show, the critical luminance increases with the viewing distance. This is probably due to the difference in sensitivity to flicker in the middle of the retina and on its periphery, as already mentioned.

The three curves relate to three different fluorescent mixtures, all giving a white luminescence. The bottom curve gives the results for a mixture of a yellow and a blue luminescent sulphide. Such a mixture is commonly used in direct-view picture tubes. The decay time of sulphides is always short (about 0.1 msec) and it is plausible that with such short decay times flicker will be most noticeable. The middle curve gives the measurements taken with a screen coated with a mixture of a yellow and a blue luminescent silicate. The yellow component has a decay time of about 5 msec, while that of the blue component is much shorter; yet the curve shows that for the mixture as a whole the critical luminance is much higher, being raised by a factor of about 2.5, regardless of the viewing distance.

With a mixture in which both the yellow and the blue components have a long decay time a still better result could be attained. This is illustrated in *fig. 4*, showing how the gain G in critical luminance (compared with a sulphide phosphor) of a single phosphor component (which in general will not give a white luminescence) with a decay time δ depends upon this decay time. Unfortunately a suitable blue phophor with long decay time has not yet been found.

The top curve in fig. 3 relates to a phosphor mixture (anti-flicker mixture) made up from three components, one of which has a decay time of about 13 msec. The critical luminances with this mixture are a factor 4.5 higher than those obtained with the sulphide mixture normally applied for direct-view picture tubes.

On the other hand, of course, the decay time must not be excessive, because otherwise rapidly moving objects in the picture would leave "trails" behind them. Further, the difference in decay time of the components of a phosphor mixture may be the cause of pictures of moving objects showing a coloured edge. These effects can, indeed, sometimes be seen but most of our observers did not notice them.

For projection-television tubes mostly the silicate mixture to which the middle curve relates is used. As regards flicker the results are then the same as in the case of direct-view tubes, provided, of course, one is looking at the projected picture; the picture on the screen of the projection tube itself flickers considerably, owing to the very high luminance.

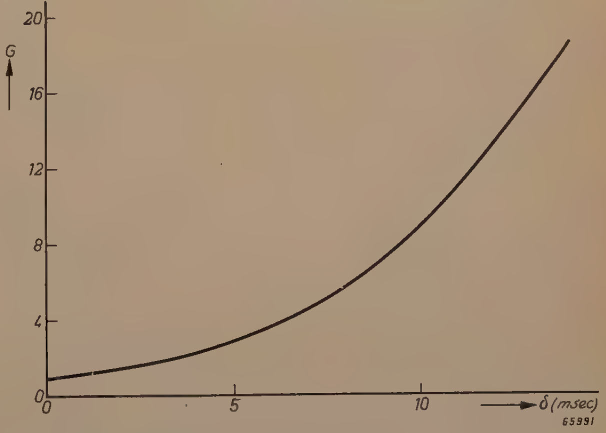

Fig. 4. The gain G in critical luminance, compared with that of a normal sulphide screen, as a function of the decay time δ of the phosphor. This diagram gives the gain for single phosphors, which therefore will not generally give white luminescence.

From the foregoing it may be gathered that with a suitable choice of the luminescent substance the permissible luminance can be raised considerably without any annoying flicker occurring.

This result is particularly of importance when we come to consider the question whether it is advisable to depart from the frame frequency of 50 c/s (with interlacing) as used in Europe and to adopt the American frequency of 60 c/s. When the critical luminance for a given phosphor and with a given viewing distance is compared for the two frequencies it appears that the gain in critical luminance that is to be reached by using the higher frequencies amounts to a factor 4.2 in the case of a sulphide mixture and a factor 5.5 when using a silicate mixture.

With the "anti-flicker mixture", however, about the same results are obtained at a frequency of 50 c/s as with a normal sulphide mixture at a frequency of 60 c/s. At a viewing distance 6 times the screen height the permissible picture luminance in the white parts is then 200 cd/m^2. Such a value is more than sufficient, even when the picture is viewed in surroundings which have not been blacked out.

Summary. The flicker of television pictures can be compared with the flicker of motion-picture projection. In both cases the perceptibility of flicker depends upon the frequency at which the pictures follow each other, the luminance of the picture and some other factors. In the case of motion-picture projection an important factor is the ratio of the intervals during which the illumination is on and off, and taking the place of this in the case of television is the decay time(s) of the phosphor mixture used for the screen of the tube. This article first deals with the origin of flicker and the properties of the eye giving rise to this phenomenon. Some laws of relationship are mentioned. Finally some experiments with television pictures are discussed, from which is appears that with a suitable choice of the fluorescent substance and when working with the European frame frequency of 50 c/s a high-light luminance of 200 cd/m^2 is permissible without causing troubleseome flicker. This value is ample for good viewing of the picture in surroundings which are not blacked out.

MEASURING THE DIELECTRIC CONSTANT AND THE LOSS ANGLE OF SOLIDS AT 3000 Mc/s

by M. GEVERS.

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The dielectric properties of solids at frequencies of some thousands of megacycles per second are interesting both from the practical point of view — since decimetric and centimetric radio waves have now found important practical applications — and from the theoretical-physical point of view, for they help in giving an insight into the structure of a solid. The method of measuring the dielectric constant and the loss angle is not new in principle but calls for an entirely new technique on account of the high frequencies occurring.

Electromagnetic waves with a wavelength of about 10 cm (frequency 3000 Mc/s) have the property of being readily focused, so that they are highly suitable for radio communications between two fixed points and for radar. Moreover, in that wave range an enormous number of channels are available and therefore there will not so readily be that "congestion" which has to be contended with nowadays on the longer wavelengths. It was a long time, however, before the technique of the decimetric and centimetric waves, or the so-called ultra-high and super-frequencies, was sufficiently mastered. The fact that this may now be said to be the case — for a number of years already — is due in part to the results of the study that has been made of the properties of various constructional materials at these frequencies.

The variation of the dielectric constant ε [1]) and of the loss angle δ as a function of the frequency has particularly been studied. When a dielectric is placed in an alternating field with an r.m.s. value E and frequency f the amount of heat generated in the dielectric per second is proportional to $E^2 f \varepsilon \tan \delta$. From the proportionality with f it follows that ε and $\tan \delta$ become particularly important at high frequencies. The amount of heat generated in a dielectric is an important point of consideration, for instance, in the choice of the kind of glass to be used for the bulb of a transmitting valve; if the right kind is not chosen the glass may melt owing to excessive dielectric losses! Other examples are to be found in the various kinds of insulators in cavity resonators, in coaxial cables and suchlike, the dielectric losses of which cause undesired damping and therefore have to be limited to the minimum. For these insulators certain plastics or materials of a ceramic nature are usually employed.

The variation of $\tan \delta$ as a function of the frequency is often erratic, so that in order to avoid unpleasant surprises the measurements have to be taken at the frequency at which the insulating material is to be used.

In this connection it is to be pointed out that knowledge of the dielectric properties of as many materials as possible in the widest possible frequency range is a matter of interest not only to the technician but also to the physicist, since it contributes towards the gaining of a better insight into the structure of solids [2]).

The method employed for measuring ε and $\tan \delta$ of solid dielectrics is a resonance method. When a rod (or disk) of the dielectric under investigation is placed in the electric field of a resonant circuit the resonance curve of that circuit undergoes a change in two respects, namely a displacement and a broadening. From the displacement it is possible to deduce the dielectric constant, and from the displacement and broadening together the loss angle can be determined [3]).

This method, in itself well-known, will first be explained under the supposition that the frequency at which the measurements are taken is not very high (say 1 Mc/s), so that a normal resonant circuit can be employed consisting of lumped inductance and capacitance. Then the modifications will be discussed which are necessary when for a frequency of, say, 3000 Mc/s the circuit has to be replaced by a cavity resonator 4).

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[1]) By ε is understood here the real part of the complex dielectric constant.

[2]) See, e.g., M. Gevers and F. K. du Pré, A remarkable property of technical solid dielectrics, Philips Techn. Rev. **9**, 91-96, 1947, dealt with more extensively in: M. Gevers, Philips Res. Rep. **1**, 197-224, 279-313, 361-379 and 447-463, 1946.

[3]) In addition to the method described here, for determining the dielectric properties of solids at high frequencies the Philips Laboratories at Eindhoven also apply a method employing wave guides. The latter method is less accurate than that described here but more suitable for still higher frequencies (10,000 Mc/s); for its description, see: H. G. Beljers and W. J. van de Lindt, Dielectric measurements with two magic tees on shorted wave guides, Philips Res. Rep. **6**, 96-104, 1951 (No. 2), and for the results of measurements taken with various kinds of glass, see: J. M. Stevels, Some experiments and theories on the power factor of glasses as a function of their composition, Philips Res. Rep. **5**, 23-36, 1950 (No. 1) and **6**, 34-53, 1951 (No. 1).

Measuring with a normal resonant circuit

In *fig. 1a* a resonant circuit is represented consisting of a coil L and an air-capacitor C. The circuit is coupled via a small capacitance C' to an oscillator O with variable frequency, and a voltmeter V is connected to the circuit via another small capacitance C''. The couplings via C' and C'' are so loose that on the one hand any variations in the circuit have no perceptible influence upon the oscillator and, on the other hand, the voltmeter does not cause any appreciable damping of the circuit.

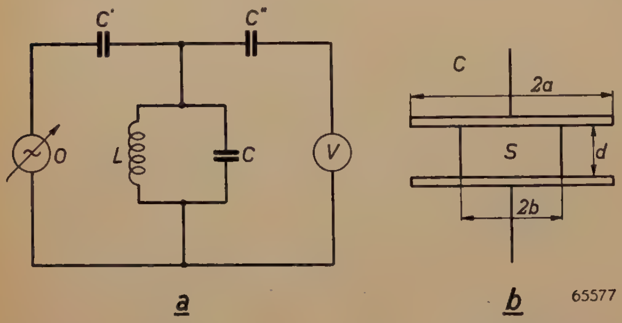

Fig. 1. *a*) A normal resonant circuit (*L-C* circuit) which can be used for measuring the dielectric constant and the loss angle at frequencies which are not excessively high. *O* oscillator with variable frequency, *V* voltmeter, *C'* and *C''* coupling capacitors with small capacitance.
b) A disk *S* of the dielectric under investigation is placed between the two electrodes of the air capacitor *C*.

A disk of the dielectric under investigation can be placed between the electrodes of the capacitor C 5). Before doing so, however, one determines with the "empty" circuit the resonant frequency f_0 at which the voltmeter shows the greatest deflection and the difference Δf_0 between the two frequencies either side of f_0 at which the voltage across the circuit is $1/\sqrt{2}$ times the maximum value. The quality factor Q_0 of the empty circuit then follows from the equation:

$$Q_0 = \frac{f_0}{\Delta f_0}\,.$$

The same measurements are then taken after having inserted between the capacitor electrodes a disk of the dielectric having exactly known dimensions (fig. 1*b*). Denoting the values then found for the resonant frequency and the width of the resonance curve by f_1 and Δf_1 respectively, the circuit quality is then

$$Q_1 = \frac{f_1}{\Delta f_1}\,.$$

Upon the dielectric being introduced the capacitance is increased from C_0 to C_1, in accordance with the formula:

$$\frac{C_1 - C_0}{C_0} = \frac{f_0^2 - f_1^2}{f_1^2}. \quad . \quad . \quad . \quad . \quad . \quad (1)$$

As we shall presently see, from the variation in capacitance it is easy to calculate ε, and from ε and the change in quality, $\tan\delta$ can be derived, taking into account the dimensions of the disk and the air capacitor, which occur in the formulae as a sort of "form factor". For these calculations it will be assumed here that the field in the capacitor is perfectly uniform (thus disregarding edge effects) and also, for the sake of simplicity, that the capacitor electrodes — two in number — and the disk are circular (with radius a and b respectively, see fig. 1*b*), that the thickness d of the disk equals the distance between the capacitor electrodes and that the "empty" capacitor is entirely free of losses.

Calculation of the dielectric constant

A capacitor with a homogeneous medium between its two electrodes (area A, distance d) has a capacitance C which is given by the equation

$$C = \varepsilon \frac{A}{d}\,,$$

where the dielectric constant ε is the product of the dielectric constant ε_0 of the vacuum and the relative dielectric constant ε_r of the medium. In the Giorgi system of units employed here $\varepsilon_0 = 10^7/4\pi c^2$, with c representing the velocity of light in vacuo $= 2.998 \times 10^8$ m/s, so that $\varepsilon_0 = 8.86 \times 10^{-12}$ F/m.

The capacitance C_0 of the "empty" capacitor ($\varepsilon_r = 1$) of the resonant circuit is therefore:

$$C_0 = \varepsilon_0 \frac{\pi a^2}{d}\,.$$

When there is inserted between the capacitor electrodes the disk with thickness d and the relative

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4) F. Horner c.s., J. Inst. El. Engrs **93** III, 53-68, 1946.

5) When measuring with a normal resonant circuit one will not actually proceed in this way, it being more usual to make from the dielectric under investigation a separate capacitor shunted across to the air capacitor. The procedure suggested in the text has only been chosen because it resembles more closely what will presently be described for the cavity resonator.

dielectric constant ε_r (to be determined), the capacitance is:

$$C_1 = \varepsilon_0 \frac{\pi a^2 - \pi b^2}{d} + \varepsilon_0 \cdot \varepsilon_r \frac{\pi b^2}{d} = \varepsilon_0 \frac{\pi}{d} (a^2 - b^2 + \varepsilon_r b^2).$$

Thus

$$\frac{C_1 - C_0}{C_0} = \left(\frac{b}{a}\right)^2 (\varepsilon_r - 1).$$

In combination with equation (1) this gives:

$$\varepsilon_r = 1 + \left(\frac{a}{b}\right)^2 \left\{ \left(\frac{f_0}{f_1}\right)^2 - 1 \right\}, \quad . \ . \ . \ . \ . \quad (2)$$

in which $(a/b)^2$ might be termed the "form factor of the dielectric constant" (or rather of $\varepsilon_r - 1$).

From the graph in *fig. 2* the value of ε_r can be found, for a given value of the parameter b/a, as a function of the ratio of the resonant frequencies f_1 and f_0.

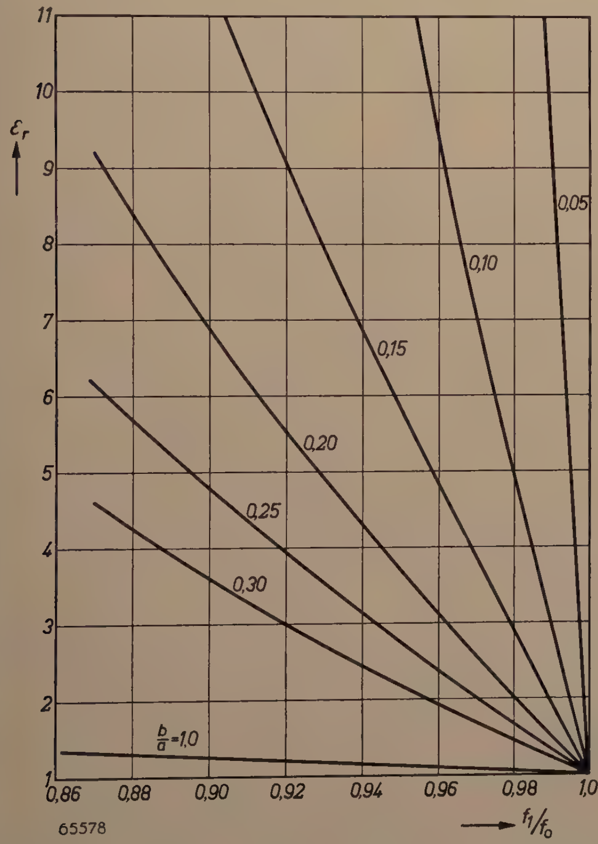

Fig. 2. The relative dielectric constant ε_r as a function of f_1/f_0, with b/a as parameter, according to the formula (2), which applies for the configuration of fig. 1.

Calculation of tan δ

The losses of a resonant circuit are inversely proportional to the quality of the circuit. As is readily understood, tan δ of the material introduced is proportional to $1/Q_1 - 1/Q_0'$, where Q_1 is the quality factor of the circuit with the dielectric in question and Q_0' is the quality factor of the circuit with an equally large disk of an imaginary dielectric having the same dielectric constant ε_r but with zero losses — the quantities Q_1 and Q_0' being measured at the resonant frequency f_1 of the circuit in both cases. Following the method described, the quality Q_1 was indeed measured at the frequency f_1 but the quality Q_0 of the empty circuit was measured at the frequency f_0. To evaluate Q_0' from the value Q_0 it should be realized that in the case of a circuit like the one considered here, where the losses are due only to the resistance R of the coil, the quality is proportional to the frequency f and inversely proportional to R. Now at high frequencies R is proportional to $\sqrt{f}$ and thus the quality is proportional to $f/\sqrt{f} = \sqrt{f}$. Hence $Q_0' = \sqrt{f_1/f_0} \times Q_0$, and

$$\tan\delta = F'\left(\frac{1}{Q_1} - \frac{1}{Q_0'}\right) \quad . \ . \ . \ . \ . \quad (3a)$$

$$= F'\left(\frac{1}{Q_1} - \sqrt{\frac{f_0}{f_1}} \cdot \frac{1}{Q_0}\right), \quad . \ . \quad (3b)$$

where F' is the "form factor of tan δ", which is equal to unity if the disk completely fills the space between the capacitor electrodes. Generally, however, (when $b < a$) there is not only a part of the capacitor with the capacitance

$$C_d = \varepsilon_0 \varepsilon_r \frac{\pi b^2}{d}$$

in which losses occur, but also a loss-free part with air as a dielectric and having the capacitance

$$C_a = \varepsilon_0 \frac{\pi a^2 - \pi b^2}{d}.$$

To find tan δ of the solid dielectric, $1/Q_1 - 1/Q_0'$ must be multiplied by $(C_d + C_a)/C_d$:

$$F' = \frac{C_d + C_a}{C_d} = \frac{\varepsilon_r b^2 + a^2 - b^2}{\varepsilon_r b^2},$$

so that equation (3b) ultimately assumes the form:

$$\tan\delta = \frac{\left(\frac{a}{b}\right)^2 + \varepsilon_r - 1}{\varepsilon_r} \left(\frac{1}{Q_1} - \sqrt{\frac{f_0}{f_1}} \cdot \frac{1}{Q_0}\right).$$

Measuring with a cavity resonator

When these measurements have to be carried out at frequencies of some thousands of megacycles per second we can no longer use a resonant circuit composed of lumped inductance and capacitance. It is most convenient to use a cavity resonator, which in our case can be a metal cylinder with a bottom and a cover. For the rest the procedure is as described above: one determines the resonant frequency and the difference between the two frequencies at which the electric (or the magnetic) field strength in the cavity resonator is $1/\sqrt{2}$ times as large as that at resonance, first with the empty resonator and then after introducing the dielectric under investigation, preferably in the form of a rod (*fig. 3*). From the measured values of f_0, f_1, Δf_0 and Δf_1 we can again derive ε_r and $\tan\delta$, though in this case the calculation is rather more complicated because the field in the cavity resonator is not even approximately homogeneous.

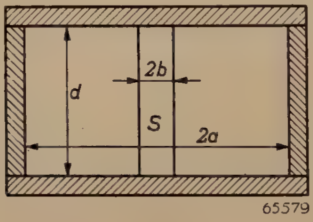

Fig. 3. A cavity resonator composed of a cylinder, bottom and cover (diameter $2a$, height d), with a rod S (diameter $2b$) of the dielectric under investigation placed inside it.

For the results of this calculation, as also for the corresponding graphs and the manner in which they are used, the reader is referred to the Appendix to this article. It may be mentioned here, however, that for $\tan\delta$ a formula is found which can be written in the form of eq. (3), viz:

$$\tan\delta = F''\left(\frac{1}{Q_1}-\frac{1}{Q_0''}\right), \quad . \ . \ . \ . \quad (4)$$

where F'' is a factor of no consequence at the moment, Q_1 is the quality factor of the cavity resonator with the dielectric introduced, and Q_0'' is a quantity which, like Q_0' in (3a), is proportional to the quality factor Q_0 of the empty resonator (or resonant circuit). The smaller the value of $\tan\delta$ to be measured accurately, the higher Q_0 has to be, so that it is of importance to consider the question of how high a quality can be reached with a cavity resonator.

The quality factor of the cavity resonator

The losses in a cavity resonator which determine its quality are the dissipative losses in the walls. The magnitude of these losses is related to the distribution of current along the walls — which, of course, differs with the infinitely large number of modes of oscillation that are possible in a cavity resonator — and to the depth of penetration of the current into the wall.

For the mode used, to which we shall revert farther on, *fig. 4* depicts the distribution of current in an arbitrary meridian plane of the empty cavity resonator. The density of current is the maximum in the cover and the bottom along a circle with a radius somewhat smaller than that of the cavity resonator. The density of current in the side wall is not much less. From this it may already be concluded that the contact resistance between the cylindrical part and the bottom or the cover should be very small.

The quality Q_0 of the empty cavity resonator is calculated from the formula:

$$Q_0 = \frac{a}{\left(1+\dfrac{a}{d}\right)\Delta_0}, \quad . \ . \ . \ . \quad (5)$$

where Δ_0 is the depth of penetration at the resonant frequency f_0, i.e. the depth to which, at that frequency, the amplitude of the current density has decreased to $1/e$ of the current density at the surface of the wall. For the penetration depth Δ at the frequency f the formula

$$\Delta = \sqrt{\frac{\varrho}{\pi\mu f}} \quad . \ . \ . \ . \ . \ . \ . \quad (6)$$

applies, where ϱ is the specific resistance and μ is the permeability of the conductor. For non-magnetic materials μ is practically equal to the permeability of the vacuum, viz. $4\pi\cdot10^{-7}$ H/m.

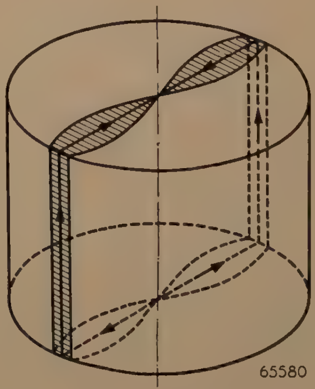

Fig. 4. The width of the hatched strip is proportional to the local current density in an arbitrary meridinal cross section of the (empty) cavity resonator (E_{010} mode, see Appendix). The arrow points indicate the direction of the current at a certain moment.

When ϱ is made as small as possible (by plating the inner walls of the cavity resonator with silver), and bearing in mind that, as we shall presently see, with the mode employed there is a fixed relationship between the radius a and the resonant frequency f_0 ($f_0 = 229.49/2a$ Mc/s, with a expressed in metres), it appears that in the formula for Q_0 only the height d of the cavity resonator is available. From this equation (5) it is seen that increasing the value of d improves the quality, but there is a limit set to the height, because if it is made too large, then other, undesired, modes may easily occur in the cavity resonator. Besides, if d is greater than a any futher increase of d would, as a matter of fact, yield only a slight improvement in quality, and moreover a tall cavity resonator with the desired extremely high quality is far more difficult to make than a low one.

Our cavity resonator has the dimensions $a = 33.5$ mm ($f_0 = 3428$ Mc/s, with corresponding wavelength λ_0 in free space 8.75 cm) and $d = 40$ mm, whilst the theoretical quality factor is $Q_0 = 17{,}560$.

Unless special precautions are taken, the actual quality obtained is usually not more than 70 to 80% of the theoretical value, as has been shown in literature ⁶). This has in fact even given rise to doubts about the correctness of the suppositions upon which formula (6) is based. However, we have found that this difference between practice and theory is due to irregularities on the inner surface of the wall causing the current to follow a longer path. Usually a cavity resonator is made by turning out a metal cylinder on a lathe, in the process of which the point of the cutter leaves more or less deep grooves in the surface at right angles to the general direction of the current (*fig. 5a*). Unless the depth of these grooves is small compared with the depth of penetration Δ the current flowing through the thin layer follows the irregularities and thus its path is considerably lengthened. It appears that polishing the surface does not improve matters much. Now from formula (6) it follows that under the given conditions the depth of penetration is about 1 μ, so that great care is certainly essential to avoid the remaining irregularities being many times greater than the penetration depth. This has been achieved in the following way ⁷).

First the brass cylinder, its bottom and cover are lined electrolytically with a layer of silver 200 μ thick. On a vibration-free precision lathe this layer of silver is then turned with a diamond having a semi-circular profile (radius of curvature about 100 μ), whilst the pitch (about 1 μ) and the shaving thickness are chosen extremely small. Since this pitch is in the order of the wavelength of light (0.4 to 0.8 μ) the surface thus turned acts as a sort of Rowland grating, showing beautiful interference rings under incident light. From the pitch and the radius of curvature it follows that the depth of the irregularities is about 10^{-3} $\mu = 10$ Å The condition at the surface is then as illustrated (for a proportionately much too small radius of curvature) in fig. 5*b*, in which case the difference to be expected from the theoretical value of Q_0 is very small. This has been confirmed by measurement: $Q_0 = 17{,}190$, which is 98% of the theoretical value! *Fig. 6* is a photograph of this cavity resonator.

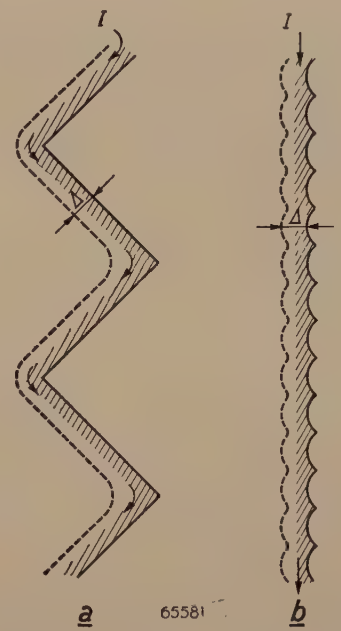

Fig. 5. Inner surface of the cavity resonator, (*a*) with sharp cutting grooves deeper than the penetration depth Δ of the high-frequency current I, (*b*) with rounded-off grooves shallower than Δ. In the case (*a*) the path of the current is lengthened considerably, whereas in the case (*b*) there is only a negligible lengthening.

In both figures the size of Δ (about 1 μ) is the same. In (*b*) the arcs have been drawn with a relatively far too large curvature (radius of curvature of the diamond cutter used was about 100 μ), so that the irregularities are relatively much exaggerated.

The bottom and the cover make such a perfect fit with the cylindrical part that the three parts laid loosely together yield the same value of Q_0 as when the bottom and cover are tightly screwed together.

The rod of the dielectric must also be turned or ground smooth and of equal thickness throughout, since its diameter must be exactly known and any irregularities in the surface would disturb the field

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⁶) In the article quoted in footnote ⁴) mention is made of a measured quality factor amounting to 72% of the theoretical value. See also E. Maxwell, Conductivity of metallic surfaces at microwave frequencies, J. appl. Phys. **18**, 629-638, 1947.

⁷) Thanks to the expert craftsmanship of Mr. L. Leblans, of Philips Research Laboratories.

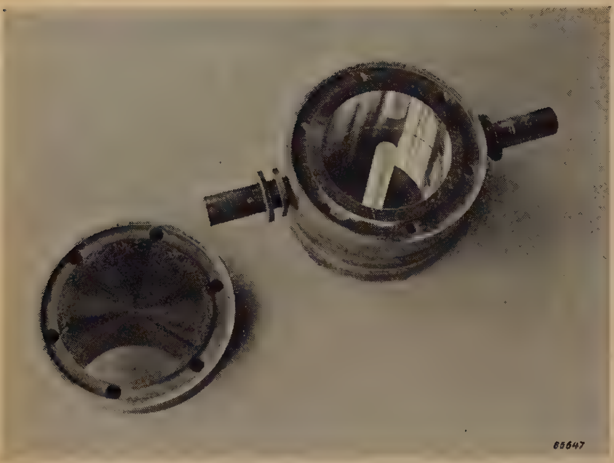

Fig. 6. The opened cavity resonator with a rod of polystyrene inside it. For the sake of clarity the boundaries between the bottom and the side of the resonator and between the rod and its reflection in the bottom have been marked in the photograph with dotted lines.

distribution, in which case the formulae given in the Appendix would apply less strictly. The length d_1 of the rod must equal the height d_0 of the cavity resonator less a certain tolerance; if d_1 were only a mere fraction of a millimetre larger than d_0 the cover would no longer fit on the cylinder, the contact resistance at the top would thereby be considerably increased and the value of Q_1 would become far too low. The centering of the rod in the resonator need not be more accurate than is possible to attain by eye.

The cavity resonator described here need be used only for materials with very low losses or in cases where the utmost accuracy is demanded. In other cases one can manage quite well with a less expensive resonator not processed with such high precision ($Q_0 \approx 9000$).

Accessory apparatus

In addition to the cavity resonator described the apparatus (*fig. 7*) comprises a calibrated oscillator and a device for measuring in a relative unit the magnetic field strength in the cavity resonator. These two components are coupled to the resonator.

As oscillator use is made of a reflex klystron (*fig. 8*), a combination of a kind of velocity-modulation tube 8) with a cavity resonator, the dimensions of which govern to some extent the oscillator frequency. With the aid of three micrometer screws — two for coarse tuning and one for fine tuning — the frequency can be varied between 3090 and 3260 Mc/s 9), thus within the range of about 10 cm waves as frequently used for radar. The frequency can be read from calibration curves.

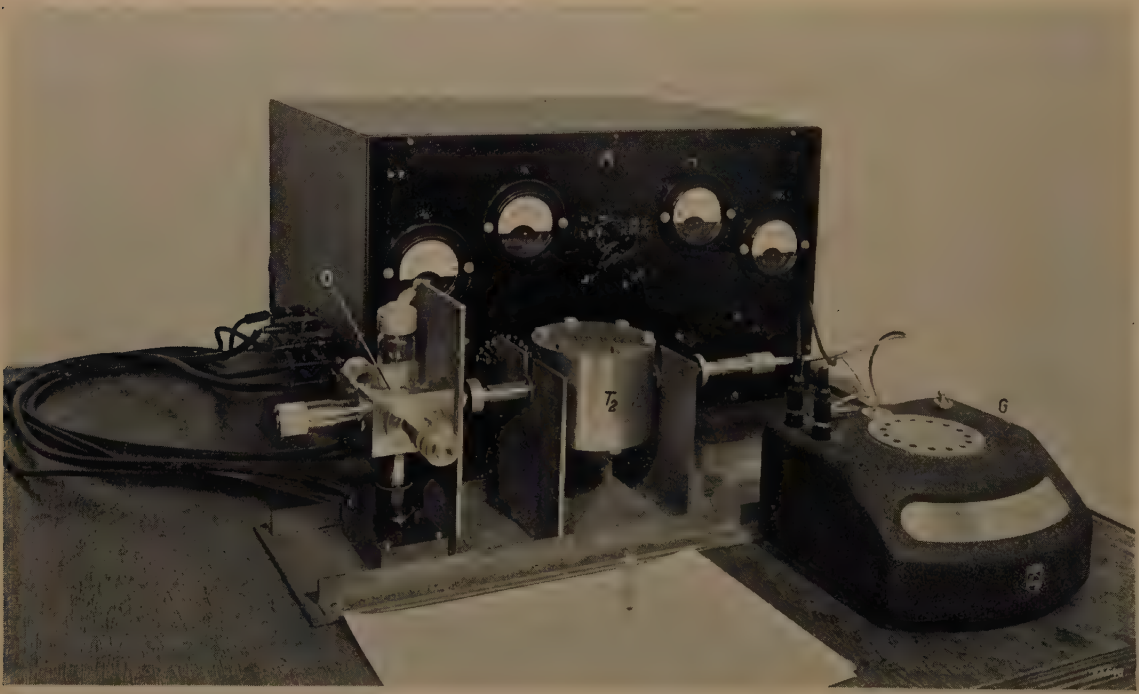

Fig. 7. Photograph of the measuring apparatus. *O* oscillator, T_2 cavity resonator, *G* galvanometer, *A* supply unit. In the foreground is a small rod of quartz prepared for insertion in the cavity resonator.

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8) Tubes of this type have been briefly discussed in the first pages of an article by F. Coeterier, Philips Techn. Rev. **8**, 257-266, 1946, and at more length in, i.a., R. H. Varian and S. F. Varian, A high-frequency oscillator and amplifier, J. app. Phys. **10**, 321-327, 1939.

9) The resonant frequency f_0 = 3428 Mc/s of the empty cavity resonator falls outside this range. This frequency and Q_0 have been determined once for all with the cavity resonator after the introduction of a rod of a material having a known dielectric constant and a known, very low, value of tan δ.

The cavity resonator used for measuring is coupled both to the resonator of the reflex klystron and to the detector. Both these couplings are made in the usual way with coupling loops and short lengths of coaxial cable. To prevent resonances occurring in the latter they are filled with a material having high dielectric losses. The couplings can be varied by rotating the loops about their horizontal axis.

The dimensions $2b$ and d of the rod are measured with a micrometer ($2b$ at different places). The diameter $2a$ of the cavity resonator must not be measured with a micrometer as otherwise the surface would be damaged. It can, however, be found by optical means, and also from the measured value of the resonant frequency (see footnote [9]); the difference in the results obtained from these two methods is less than 0.01%.

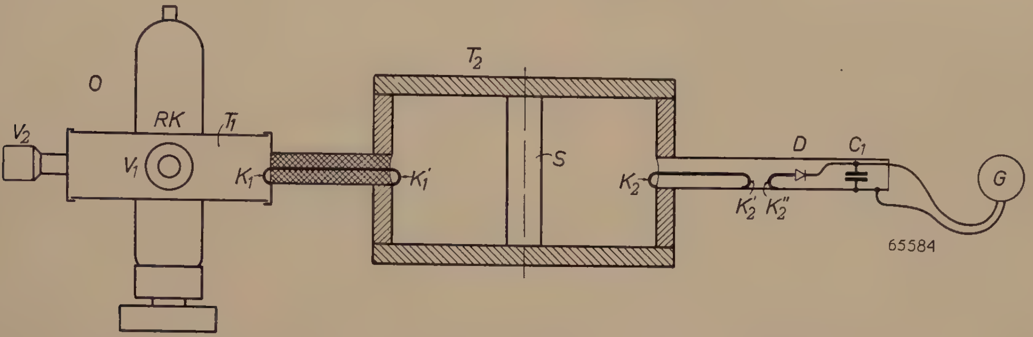

Fig. 8. Schematic representation of the measuring apparatus. O oscillator, with reflex klystron RK having a cavity resonator T_1 which can be tuned with the knobs V_1 (coarse) and V_2 (fine). T_2 is the measuring cavity resonator, with rod S of the material under investigation. The coupling loops K_1 and K_1' couple T_1 to T_2; the loops K_2, K_2' and K_2'' couple T_2 to the detector D. C_1 is a smoothing capacitor. G the galvanometer.

The detector is a silicon crystal. This supplies a rectified current which, after being smoothed by a capacitor, flows through a sensitive galvanometer (full deflection at 1 μA, resistance 1000 ohms). The characteristic of the crystal is such that the deflection of the meter is practically proportional to the square of the magnetic flux embraced by the coupling loop K_2. When the quality factor is being measured the oscillator is therefore detuned until the deflection is half the value at resonance.

Accuracy

The accuracy with which the values of ε_r and of $\tan\delta$ can be measured depends upon the accuracy and the constancy of the frequency calibration, the exactness of the dimensions given and the extent to which the cavity resonator and the rod deviate from the rotationally symmetrical shape.

With the aid of a frequency meter (accuracy about $1:10^6$) the oscillator is first calibrated at different positions of the knobs for coarse tuning and a fixed position of the knob for fine tuning. Then, for a number of positions of the first-mentioned knobs, the detuning which can be brought about with the fine-tuning knob is calibrated (accuracy $1:200$). It has been found that in a period of two years the oscillator calibrations showed praccally no change.

In general, with the apparatus described, an accuracy of ± 1% can be reached for the dielectric constant, whilst for $\tan\delta$ the accuracy is ± 1% $\pm 0.2\times10^{-4}$ (the latter figure is the absolute error.)

The table below gives a few of the results of a number of measurements, carried out at a frequency of approximately 3100 M/cs (wavelength between 9.7 and 9.5 cm). It is particularly to be noted that very small values of $\tan\delta$, such as those of polythene and quartz glass, can be accurately measured. For comparison the values of $\tan\delta$ at 1.5 Mc/s are also shown.

Frequency in Mc/s	3100		1.5
	ε_r	$\tan\delta\cdot10^4$	$\tan\delta\cdot10^4$
Some samples of glass			
A hard glass	4.20	64.8	36.4
Two kinds of lead glass	6.30	61.7	20.2
	7.15	44.4	8.9
Quartz glass	4.20	0.8	0.8
Some samples of plastics			
Polystyrene	2.52	2.6	2.4
Polythene	2.25	2.0	2.0
"Plexiglass" or "Perspex"	2.6	64.1	130

Appendix

Field distribution in the cavity resonator

By a suitable method of exciting the cavity resonator (not made too tall — see above) it is ensured that of all the possible modes only the E_{010} mode [10]) occurs, the resonant frequency of which depends solely upon the radius a of the cylinder. The first nought in the index following E means that the electric and the magnetic fields in the cavity resonator are independent of the cylinder coordinate φ (see *fig. 9*), and hence that the fields are rotationally symmetrical. The second nought indicates that the fields are independent of the coordinate z. The figure 1 in the index will be explained later.

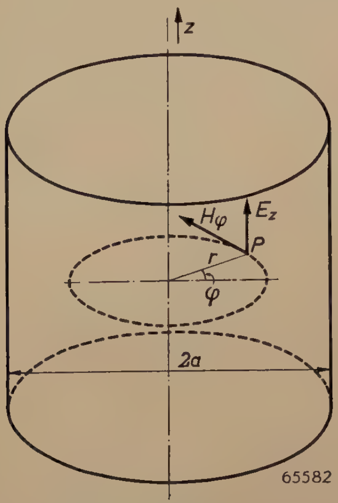

Fig. 9. Cylindrical cavity resonator with cylinder coordinates r, φ and z. In the case of the E_{010} mode, at any point P the quantities E_z and H_φ are the only components of the electric and magnetic fields respectively.

The E_{010} mode can be described with one component of the electric field and one component of the magnetic field, each of which depends upon only one space coordinate, r. These components are E_z, which runs parallel to the z-axis, and H_φ, which runs tangentially (fig. 9). H_φ and E_z of the empty cavity resonator are represented by the following equations:

$$\left.\begin{aligned} H_\varphi &= \phantom{\frac{k_0}{\mathrm{j}\omega_0\varepsilon_0}} A\,\mathrm{J}_1(k_0r)\cos\omega_0t,\\ E_z &= \frac{k_0}{\mathrm{j}\omega_0\varepsilon_0}\,A\,\mathrm{J}_0(k_0r)\cos\omega_0t.\end{aligned}\right\}\quad .\ .\ (7)$$

where A is a proportionality factor depending upon the power of the oscillator and the coupling between the oscillator and the cavity resonator, and $k_0 = 2\pi/\lambda_0$. The factors J_0 and J_1 are Bessel functions of the first kind, respectively of the order 0 and 1, whilst $\cos\omega_0t$ denotes the dependency upon the time t; ω_0 is the angular frequency at which the empty cavity resonator resonates.

The boundary condition is that the electric field strength is zero at the wall of the cavity resonator (the wall assumed to be of infinite conductivity), so that $E_z = 0$ for $r = a$. The first root of $\mathrm{J}_0(k_0a) = 0$ is $k_0a = 2.4048$, thus the first resonant wavelength $\lambda_0 = 2\pi a/2.4048 = 2.6125a$ and the first resonant frequency $f_0 = c/\lambda_0 = 229.49/2a$ Mc/s, a being expressed in metres. (The figure 1 in the index of E_{010} denotes that this first resonance is meant.) Thus, for instance, with the diameter of 67 mm chosen by us the resonant frequency $f_0 = 3428$ Mc/s, as already mentioned.

The graphs in *fig. 10* show how the amplitudes $E_{z\,\max}$ and $H_{\varphi\,\max}$ of the field quantities vary with the distance r from the axis of the cavity resonator.

From the calculation of the inhomogeneous field distribution in the cavity resonator with a rod placed inside it, the following (approximate) formula is found for ε_r:

$$\varepsilon_r = 1 + \frac{M-1}{1+\dfrac{k_1'^2b^2}{8}M}\quad .\ .\ .\ .\ .\ (8)$$

where $k_1' = 2\,\pi f_1/c$ and M is an expression in which Bessel functions with the arguments $k_1'a$ and $k_1'b$ occur (see the formula (12) below).

Calculation of ε_r

The deduction of the formula (8) is in broad lines as follows: For the inside of the dielectric, thus for $0 \leqq r \leqq b$, we have:

$$\left.\begin{aligned} H_\varphi &= \phantom{\frac{k_1''}{\mathrm{j}\omega_1\varepsilon_0\varepsilon_r}} A\,\mathrm{J}_1(k_1''r)\cos\omega_1t,\\ E_z &= \frac{k_1''}{\mathrm{j}\omega_1\varepsilon_0\varepsilon_r}\,A\,\mathrm{J}_0(k_1''r)\cos\omega_1t.\end{aligned}\right\}\quad .\ .\ .\ (9)$$

These equations differ from (7) in that k_0 is replaced by a quantity $k_1'' = k_1'\sqrt{\varepsilon_r} = 2\pi f_1\sqrt{\varepsilon_r}/c$ and ω_0 by the resonant angular frequency ω_1, whilst in the denominator of the expression for E_z a factor ε_r has been added. (In these equations it has been assumed that H_φ and E_z are not affected by the losses in the material, an assumption which is justified except in the case of very poor dielectrics.)

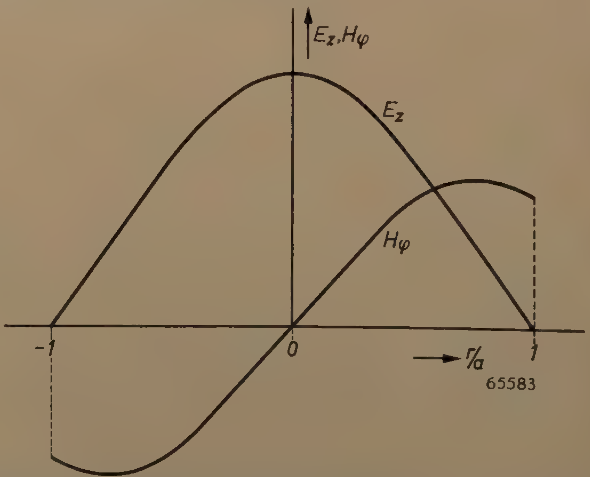

Fig. 10. Distribution of $E_{z\,\max}$ and $H_{\varphi\,\max}$ along a diameter of the cavity resonator in the E_{010} mode.

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[10]) For "E-waves", also called "TM-waves", see, e.g., W. Opechowski, Electromagnetic waves in wave guides, Philips Techn. Rev. 10, 46-54, 1948, and in particular pp 50 and 51.

In the remaining part of the cavity resonator ($b \leqq r \leqq a$) the following equations apply:

$$\left.\begin{aligned} H_\varphi &= \left\{B\,\mathrm{J}_1(k_1'r) + C\,\mathrm{Y}_1(k_1'r)\right\}\cos\omega_1 t, \\ E_z &= \frac{k_1'}{\mathrm{j}\omega_1\varepsilon_0}\left\{B\,\mathrm{J}_0(k_1'r) + C\,\mathrm{Y}_0(k_1'r)\right\}\cos\omega_1 t, \end{aligned}\right\} \quad . \quad (10)$$

where Y_0 and Y_1 are Bessel functions of the second kind, respectively of the order 0 and 1. The constants B and C are proportional to A and can be eliminated with the aid of the boundary conditions. These are as follows: for $r = a$ again E_z must equal 0, and at the boundary between the solid dielectric and air E_z and H_φ must be continuous, which means to say that for $r = b$ the equations (9) must yield the same values for E_z and H_φ as those yielded by the eqs (10).

From the first boundary condition it follows that:

$$B\,\mathrm{J}_0(k_1'a) + C\,\mathrm{Y}_0(k_1'a) = 0,$$

and from the second boundary condition, in so far as the continuity of E_z is concerned,

$$\frac{k_1''}{\varepsilon_r} A\,\mathrm{J}_0(k_1''b) = k_1'\left\{B\mathrm{J}_0(k_1'b) + C\mathrm{Y}_0(k_1'b)\right\},$$

and as regards the continuity of H_φ,

$$A\mathrm{J}_1(k_1''b) = B\mathrm{J}_1(k_1'b) + C\mathrm{Y}_1(k_1'b).$$

By eliminating B/A and C/A from these three equations we find:

$$\varepsilon_r = \frac{k_1'' \cdot \mathrm{J}_0\,(k_1''b) \cdot \mathrm{J}_1\,(k_1'b)}{k_1' \cdot \mathrm{J}_1\,(k_1''b) \cdot \mathrm{J}_0\,(k_1'b)}\,M, \quad . \;.\; . \quad (11)$$

in which

$$M = \frac{\dfrac{\mathrm{Y}_0(k_1'a)}{\mathrm{J}_0\,(k_1'a)} - \dfrac{\mathrm{Y}_1(k_1'b)}{\mathrm{J}_1\,(k_1'b)}}{\dfrac{\mathrm{Y}_0(k_1'a)}{\mathrm{J}_0\,(k_1'a)} - \dfrac{\mathrm{Y}_0(k_1'b)}{\mathrm{J}_0\,(k_1'b)}} \quad . \;.\; .\; .\; .\; . \quad (12)$$

In (11) ε_r occurs implicitly in the fraction preceding M, namely in the factor k_1''. If, however, $b\sqrt{\varepsilon_r}$ is very small compared with a, this fraction can be approximated by

$$1 - \frac{(k_1'b)^2}{8} \cdot (\varepsilon_r - 1),$$

so that (11) is then simplified into:

$$\varepsilon_r \approx \left\{1 - \frac{(k_1'b)^2}{8}(\varepsilon_r - 1)\right\} \cdot M.$$

Solving this equation for ε_r leads to eq. (8).

The formula (8) holds to a good approximation only as long as $b\sqrt{\varepsilon_r} \ll a$ (e.g. $< 0.2\,a$). Most of the solid dielectrics that can be considered for use at frequencies in the order of 1000 Mc/s have a relative dielectric constant between 2 and 10. From the condition just mentioned it follows that the diameter of the rod must be smaller than 1/7th to 1/16th of the diameter of the cavity resonator.

The rod has to be much thinner still when taking measurements with materials such as barium titanate, where ε_r may be in the order of 1000 [11]). The cavity resonator described could be made suitable for such cases by drilling a small hole in the centre of the cover and the botton and inserting the dielectric in the form of a wire (thinner than 1 mm) through those holes.

In *fig. 11* a series of curves are given representing ε_r as a function of $k_1'a$, according to eq. (8), with b/a as parameter. Since $k_1'a = 2\pi a f_1/c$, the abscissa is directly proportional to the resonant frequency f_1 of the cavity resonator with the rod in it. For a certain cavity resonator, with given a, the constant $2a\pi/c$ can be incorporated in the scale units.

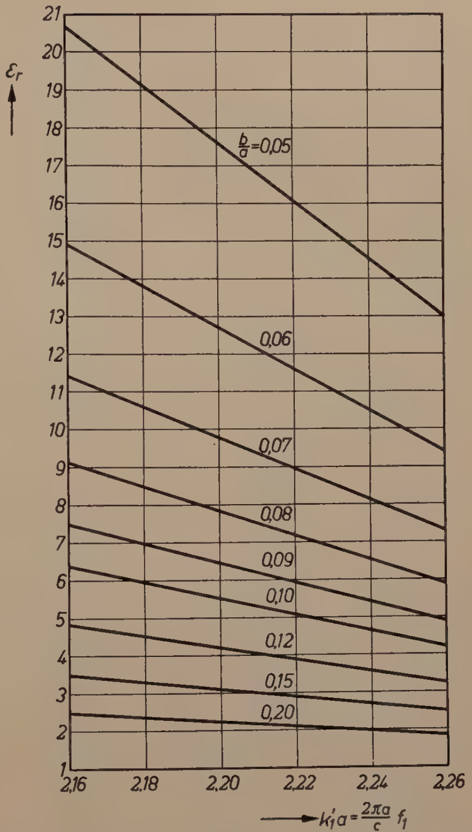

Fig. 11. The relative dielectric constant ε_r as a function of $2\pi a f_1/c$, with b/a as parameter, according to formula (8); configuration as in fig. 3.

The calculations for $\tan\delta$ — which will not be given here — yield the following formula (cf. formula (4)):

$$\tan\delta = \frac{\left(\dfrac{a}{b}\right)^2 D + \varepsilon_r - 1}{\varepsilon_r\left[1 + \left\{\dfrac{\mathrm{J}_1\,(k_1''b)}{\mathrm{J}_0\,(k_1''b)}\right\}^2\right]} \cdot \left(\frac{1}{Q_1} - \frac{1}{Q_0''}\right), \quad (13)$$

where D stands for the expression:

$$D = \left[\frac{2}{\pi k_1'a} \cdot \frac{1}{\mathrm{Y}_0(k_1'a)\,\mathrm{J}_0(k_1'b) - \mathrm{Y}_0(k_1'b)\,\mathrm{J}_0(k_1'a)}\right], \quad \ldots \quad (14)$$

which is represented in *fig. 12* as a function of $k_1'a$ $(= 2\pi a f/_1 c)$ with b/a as parameter. *Fig. 13* is a graph representing as a function of $k_1''b (= 2\pi b\sqrt{\varepsilon_r} f_1/c)$ the term $(\mathrm{J}_1/\mathrm{J}_0)^2$ occurring in the formula (13).

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[11]) G. H. Jonker and J. H. van Santen, The ferro-electricity of titanates, Philips Techn. Rev. **11**, 183-192, 1949.

By analogy with the quantity Q_0' occurring in the *L-C* circuit, the quantity Q_0'' occurring in eq. (13) is understood to be the quality factor at the frequency f_1 if there were to be introduced in the cavity resonator a rod of a hypothetical loss-free dielectric of the same dimensions and with the same dielectric constant as the rod of the material under investigation. Calculations yield for $1/Q_0''$:

$$\frac{1}{Q_0''}=\sqrt{\frac{f_0}{f_1}}\cdot\frac{a}{a+d}\cdot\left\{1+\frac{\frac{ad}{b^2}D}{\left(\frac{a}{b}\right)^2 D+\varepsilon_r-1}\right\}\cdot\frac{1}{Q_0}. \quad (15)$$

This form is more complex than the relationship between $1/Q_0'$ and $1/Q_0$ for the normal resonant circuit, due to the fact that in the case of the circuit the dissipative losses in the capacitor electrodes can be ignored, whereas in the case of the cavity resonator owing to the introduction of the dielectric the current distribution is changed and thus also the dissipative losses are different.

Recapitulating, the procedure is as follows: From graphs like those in figs 11 and 12 we read the relative dielectric constant ε_r and the quantity *D*, respectively, for the measured resonant frequency f_1 and the value chosen for b/a. With *D*, the measured values f_0, f_1, $Q_0 = f_0/\Delta f_0$ and the dimensions *a*, *b* and *d*, we calculate $1/Q_0''$ according to the formula (15), and from the graph of fig. 13 we read the quantity $(J_1/J_0)^2$ for the calculated value of $k_1''b = 2\pi b\sqrt{\varepsilon_r} f_1/c$. We then have all the data required to calculate $\tan\delta$ from eq. (13).

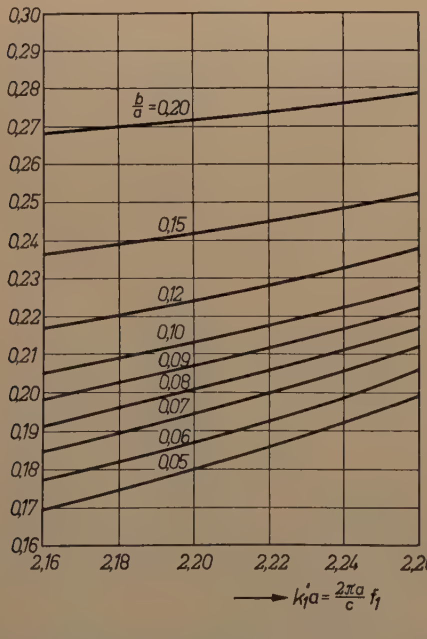

Fig. 12. The quantity *D*, according to (14), as a function of $2\pi a f_1/c$, with b/a as parameter.

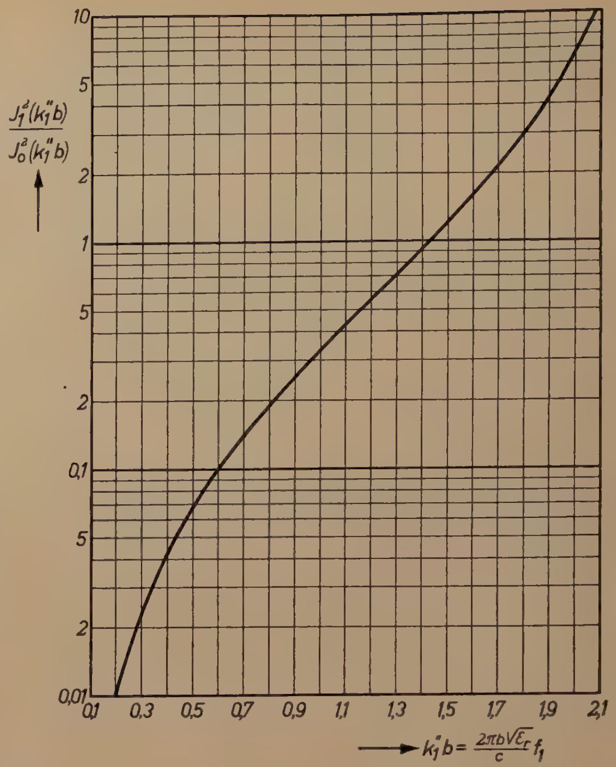

Fig. 13. The quantity $J_1^2(k_1''b)/J_0^2(k_1''b)$ occurring in formula (13), as a function of $k_1''b$.

Summary. The relative dielectric constant ε_r and the loss angle δ of a solid dielectric are determined from the detuning and the reduction of the quality factor to which a resonant circuit is subject when the dielectric is introduced in the electric field of the circuit. Owing to the high frequency at which the measurements are taken (about 3000 Mc/s) a cavity resonator is employed instead of a normal resonant circuit. This is cylindrical in shape and resonates in the E_{010} mode. For accurately measuring $\tan\delta$ of materials with very low losses it is necessary that the quality of the cavity resonator prior to the introduction of the dielectric should be extremely high. The quality factors hitherto reached were never higher than 70 to 80% of the theoretical value. This is ascribed to the fact that the irregularities left in the inner surface of the cavity resonator after the mechanical processing are greater than the penetration depth of the current (1 μ) and thus cause the path followed by the current to be considerably lengthened. By extremely careful finishing of this surface it has now been possible to reduce the depth of these irregularities to the order of 10^{-3} μ, thereby raising the quality factor (17,190) to 98% of the theoretical value.

As oscillator a reflex klystron is used, the frequency of which is variable within a certain range (3090-3260 Mc/s). The calibration has proved to be highly constant. As detector a silicon crystal is used, connected to a galvanometer.

A table is given showing some measured values of ε_r and $\tan\delta$ for a number of materials at a frequency of over 3000 Mc/s. The accuracy of the measurements for ε_r is ± 1% and that for $\tan\delta$ is $\pm 1\% \pm 0.2\times10^{-4}$. In an appendix formulae and graphs are given with the aid of which ε_r and $\tan\delta$ can be determined from the quantities measured.

SPECIAL X-RAY TUBES

by B. COMBÉE and P. J. M. BOTDEN. 621.386.1 : 616-073.75 : 615.849

As in most branches of technical engineering, also in the field of the application of X-rays there is to be seen side by side a development of fundamentally new possibilities — of those of recent date we would mention only the use of the electron image amplifier and of modern electron accelerators — and a further development of existing instrumentarium. As far as the latter development is concerned, in many constructions, in particular of X-ray tubes for special applications, there is a gradual quantitative progress to be observed, which is the fruit of continued research in regard to the materials used and the shaping of the products.

Reviewing the course of development of X-ray tubes up to the present day, a parallel is to be found with the development of the incandescent lamp. In both cases there was first a period of several decades marked by a wrestling with technical problems which ultimately led to the mastery of the physical and technological fundamentals of the product. This was followed by a period in which the field of application was widened by the development of a number of modifications of stabilized prototypes in order to meet the needs of special applications. In the case of the incandescent lamp this led to hundreds of different kinds of "special lamps" being produced, and although we cannot speak of hundreds there are nevertheless quite a respectable number of special X-ray tubes too, differing greatly in appearance and also in their properties. To determine roughly the scope covered by the latter we could take as the mean a normal, universal tube for X-ray diagnostics and a normal 250 kV therapy tube, and take as the extremes the tubes for diffraction radiographs with hours of exposure and the tubes for instantaneous X-ray photographs with an exposure of 10^{-6} sec, the miniature tubes for dental apparatus and tubes for examining materials with tensions of 2 million volts. (Here we leave out of consideration the generation of extremely hard X-rays, for example, by means of linear accelerators, betatrons or synchrotrons and suchlike, to which the conventional conception of an "X-ray tube" no longer applies.)

In this article a few examples will be taken from the store of modern X-ray tubes and it will be shown how, by the application of the materials now available and by the use of modern methods, it has been possible so to improve the construction of X-ray tubes as to make them more suitable for certain special purposes. First we shall discuss a diagnostic tube, the "Rotalix" 0-55, and then two therapeutic tubes, the new CT tube for contact therapy and the ET tube for endotherapy.

The "Rotalix" 0-55

The principle of the rotating anode, which has been applied in the "Rotalix" tube and was first put into practice by Bouwers [1]), has repeatedly been dealt with in this journal [2]). It is recalled that the motive for causing the anode to rotate lies in the increased specific loading capacity of the focal spot. To take an X-ray photograph of a part of the body that is in motion the exposure time has to be as short as possible, so that a great intensity of X-rays is desired, thus a large power on the anode. On the other hand, the focus, from which the X-rays emerge and in which the power from the bombardment by the stream of electrons is for the greater part converted into heat, has to be kept very small so as to limit the kinetic blurring of the X-ray image. Owing to the rotation of the anode the area bombarded by the electrons during the exposure is increased without enlarging the focus, so that for a given permissible focus temperature the focus can be more heavily loaded.

At first this improvement was applied only in X-ray tubes for diagnostic apparatus that was required to meet the highest demands. To put it more concretely, the "Rotalix" tubes hitherto produced were high-power tubes intended to be D.C. fed. The latter fact results from the former since large diagnostic installations are always D.C. fed, on the one hand because this is the most rational method of generating X-rays [3]), and on the other hand because the additional cost of the high-tension valves etc. weighs relatively little in the case of large installations.

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[1]) A. Bouwers, Physica **10**, 125, 1930.

[2]) J. H. van der Tuuk, Philips Techn. Rev. **3**, 292-298, 1938 and **8**, 33-41, 1946.

It having come to be the common practice to use the rotating anode for large X-ray diagnostic apparatus, it was only natural to introduce this refinement also in simpler installations working at a lower rating and with a self-rectified X-ray tube. Thus the "Rotalix" O-55 was designed, which is illustrated in *figs 1* and *2*.

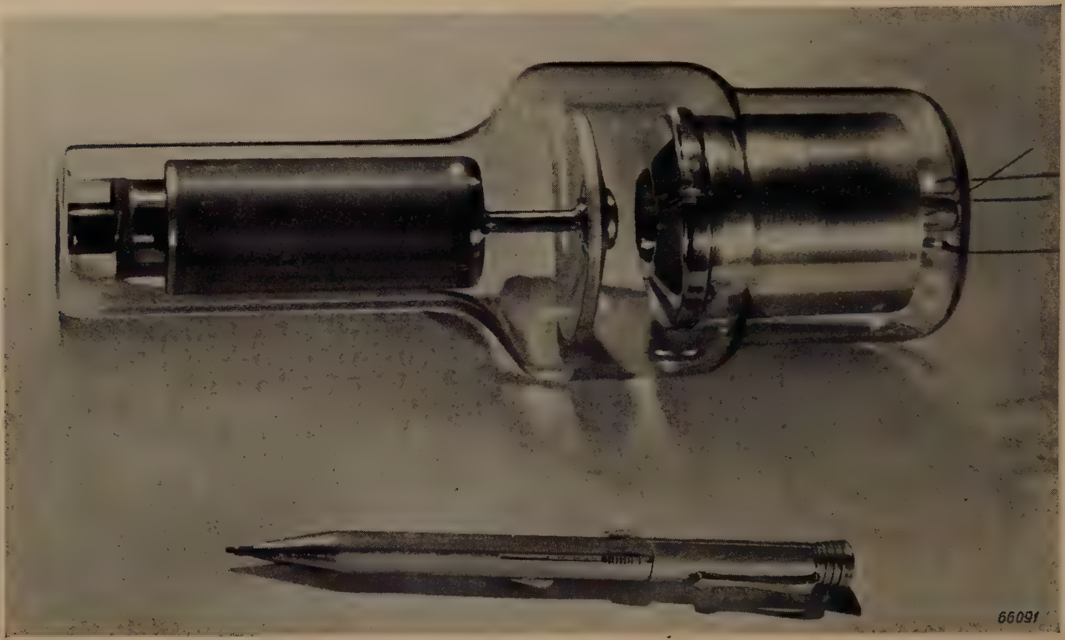

Fig. 1. The "Rotalix" O-55.

Before proceeding to discuss this tube (or at least the details in which it differs from the older types of "Rotalix" tubes) it has to be considered what purpose is served in making the anode of a self-rectified X-ray tube rotate.

Confining our considerations to exposures in the order of 0.1 sec, for which the question of the specific loading capacity of the focal spot is of most importance, it may be said that when working with direct voltage or with full-wave rectified, non-smoothed alternating voltage (*fig. 3a*), the loading capacity of a rotating-anode tube is 8 to 9 times that of a stationary-anode tube. In the case of self-rectified operation (fig. 3*b*) one would at first sight expect the improvement in this respect to be much less, since between two successive current peaks the focus has an opportunity to cool down; to put it in other words, as the anode is rotated there is always some part of the focal spot track that is not bombarded at all by the electrons. Roughly speaking, it might therefore be supposed that the increase in the loading capacity due to rotation of the anode would amount to no more than a factor 4.

A closer investigation, however, shows that this argument is not quite correct. In the above-mentioned gain of 8 to 9, as applying to D.C. operation, it is assumed that the maximum permissible focus temperature is not influenced by the rotation of the anode. This is indeed the case when the tube is D.C. operated; the focus temperature is then only limited by the mechanical stresses resulting in a gradual roughening of the anode surface (cracking). In the case of self-rectified operation, however, account has also to be taken of the risk of backfiring. As a consequence of this, in the case of a stationary anode, the maximum permissible focal temperature is much lower than when the tube is D.C. operated: in the negative half-cycle, i.e. when the anode is negative and the filament positive, the focus must not be allowed to become so hot as to emit electrons to any appreciable extent, because these would impinge upon the filament with considerable energy and soon destroy it [4]). It is true that in the 0.005 sec between the current peak in the positive half-cycle and the beginning of the negative half-cycle the focus cools down some hundreds of degrees, but the temperature limit below which thermionic emission becomes harmless lies so much lower than the limit set by the surface roughening of the anode that, in the case of self-rectified operation, the permissible loading capacity of the focal spot is only about half that in the case of operation with a full-wave rectified voltage. When the anode is made to rotate instead of being stationary the problem of backfiring at once assumes a different aspect. Those parts of the anode which are intensively heated in the positive half-cycle are no longer facing the filament in the negative half-cycle, since meanwhile the anode has turned (it is caused to rotate at the rate of almost 50 rev./sec). Consequently any electrons emitted by the anode in the positive half-cycle do not impinge upon the filament but can be intercepted by parts of the tube where they can do no harm. Thus it is possible to work with a higher temperature in the negative half-cycle than is permitted when the anode is stationary, and this favourable factor, added to the fact that in the time interval of 0.005 sec following the peak load the part of the anode in question has much better opportunity to cool down than when it is in the stationary state [5]), allows of practically the same gain in loading capacity being attainable with alternating-voltage as with direct-voltage supply.

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[3] In self-rectified operation, for the same maximum permissible current (peak value) — determined mainly by the mains — the intensity of radiation obtained is only half that when operating with two-phase rectified voltage. For high powers self-rectified operation is also less suitable owing to the asymmetry of the voltage variation (heavy voltage drop in the half-cycle where the X-ray tube passes current). Finally the yield of X-rays per watt is greater when using a rectified, smoothed voltage than in the case of self-rectified operation.

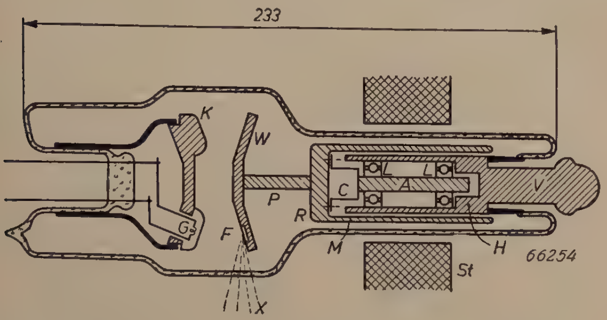

Fig. 2. Cross section of the "Rotalix" O-55. The filament *G*, placed in a slot in the cathode plate *K*, emits the electrons, which (during the positive half-cycle) are accelerated by the tube voltage and impinge upon the rotating anode, made in the form of a disk of tungsten (*W*), in the focus *F*. Under the electron bombardment this disk becomes red hot and a large part of the heat generated is carried off by radiation. Cooling by radiation is further promoted by the blackened copper sleeve *M* of the rotor *R*, to which the disk is connected by the thin molybdenum pin *P*. The rotor is driven by the rotating field of the stator winding *St* placed round the anode neck of the X-ray tube. The spindle *A*, connected to the rotor via a thin cylindrical part *C*, rotates in ball-bearings *L* lubricated with lead and fixed in the anode support *H*. This support is fused by means of a "Kovar" ring into the hard-glass wall of the tube and with the extension *V* forms the pole for connecting the anode to the high tension. *X* is the effective cone of X-rays.

Of course, even in this favourable situation as regards backfiring every precaution must be taken to limit or render harmless any electron emission from the anode. In the process of manufacture steps are taken to keep the anode as free as possible of impurities, particularly those with a low work function, which would most readily give rise to thermionic emission. Furthermore, every tube is specially tested for the occurrence of anode emission. To provide against the consequences of an increase in anode emission during the lifetime of the tube, the glass wall — which, next to the filament, is most sensitive to electron bombardment — is protected by giving the cathode plate a much larger diameter than in the case of the normal "Rotalix" tubes (see fig. 2). The configuration of anode and cathode is made so favourable, as regards the maximum local field strengths, that the tube can safely be operated with an alternating voltage of 100 $\mathrm{kV_{peak}}$; when working with a rectified voltage, which of course is also possible, one can go up to 110 $\mathrm{kV_{peak}}$.

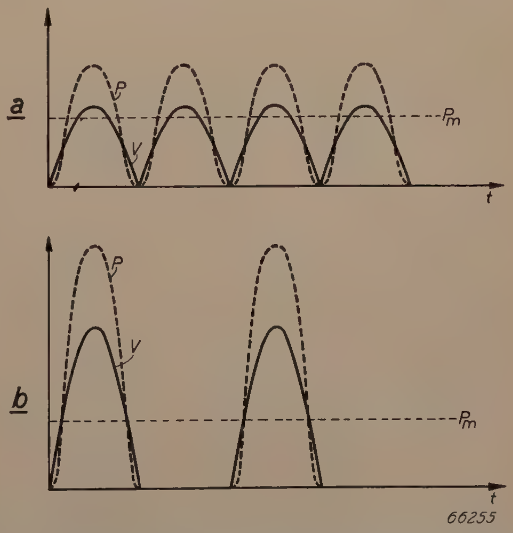

Fig. 3. Variation, as a function of the time *t*, of the instantaneous values of the voltage *V* and the power *P* of an X-ray tube:
a) when operating with full-wave rectified alternating voltage;
b) in self-rectified operation with the same mean power P_m.

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[4]) For a more detailed discussion of backfiring see, e.g., J. H. van der Tuuk, Philips Techn. Rev. **6**, 309-315, in particular p. 311.

[5]) In 0.005 sec it has rotated through an arc equal to several times the width of the focus, so that after 0.002 sec it will already be out of the range of the electron beam. For a more detailed discussion of the cooling problem see W. J. Oosterkamp, Philips Res. Rep. **3**, 303, 1938.

In a "Rotalix" tube for D.C. operation the anode is rotated only during an exposure. For screening, which is done with the same tube but with a much lower load on the focus, no purpose is served by rotating the anode and it is therefore kept stationary, to save the bearings from unnecessary wear. With the "Rotalix" tube for self-rectified operation, however, it is a different matter, for in this case the rotation of the anode performs an important function in counteracting backfiring, so that the anode must always rotate, even when screening. To make this possible the bearing construction has been modified, compared with that in the old type of tube. In particular the anode support (*H* in fig. 2) carrying the ball races for the rotating anode is now made entirely of iron; formerly it was made of copper, with an iron jacket round it for concentrating as far as possible in the rotor of the anode the magnetic field of the stator winding round the X-ray tube. The new construction has greater mechanical strength and thus easily permits of continuous rotation of the anode, even between successive screenings and radiographing, so that the operating apparatus can be simplified. It is true that the conduction of heat through the iron anode support to the oil in the shield, in which the whole tube is contained, is less satisfactory than with a copper support. However, the necessary low temperature of the bearings is maintained by the thermal resistance provided by a thin-walled cylindrical part connecting the chrome-iron spindle to the rotor sleeve of the anode (see *C* in fig. 2).

Since the "Rotalix" O-55 is intended for small installations it was desired to make the dimensions both of the tube and of the shield much smaller than those of the older type of "Rotalix" tubes. As far as the tube is concerned, the tungsten disk of the anode has been given a smaller diameter (55 instead of 75 mm), thus sacrificing a small part (factor 1.2) of the aforementioned gain in loading capacity of the focal spot. Further, the rotor sleeve is narrower, so that the stator winding to be passed round the tube at this part could be given a much smaller external diameter, whilst, finally, the rotor and thus the whole tube is made slightly shorter. As a result also the shield could be made much smaller (*fig. 4*).

The surface and wall temperature of the shield determine the power that it is permissible to generate in the X-ray tube under continuous operation. Owing to a highly heat-resistant material being used for the insulators, and especially for male and female plugs with which the tube is connected to the high tension supply, the oil and the wall of the shield may be permitted to reach very much higher temperatures than before, viz 100 °C to 110 °C compared with 60 °C to 70 °C, so that the apparatus can be operated with a continuous power of 210 watts (the tube itself can withstand 350 watts continuously).

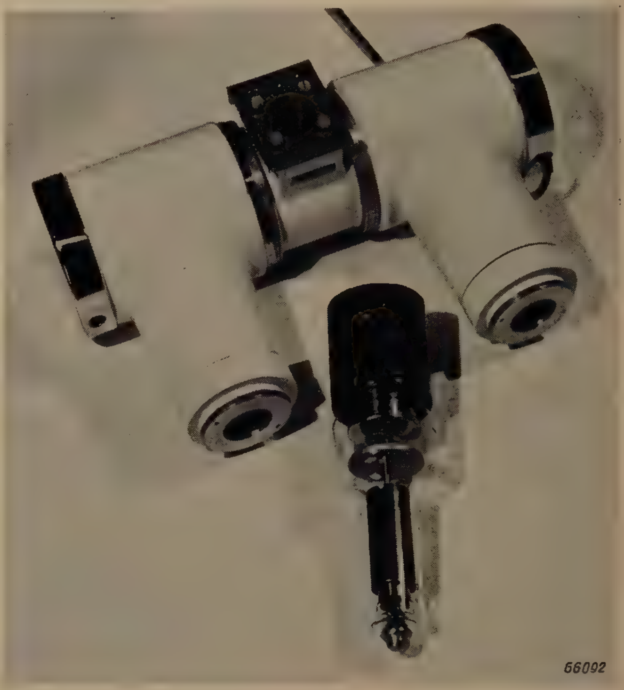

Fig. 4. Shield of the "Rotalix" O-55. In the foreground the tube itself, fitted with a "Philite" cap enveloping the cathode connection.

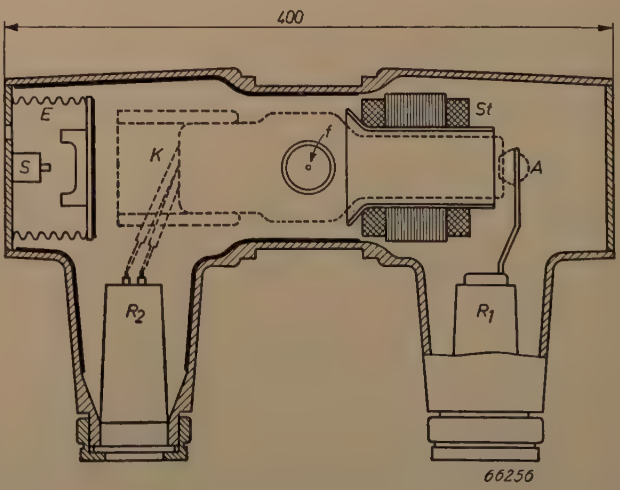

Fig. 5. Cross section of the shield of the "Rotalix" O-55. The tube is outlined in broken lines; the focus lies exactly in the middle, at *f*. *A* anode pole, *K* cathode pole, with female plugs R_1, R_2 for connecting the high-tension cables. *St* stator winding. *E* expansion chamber, taking up the thermal expansion of the oil, with safety switch *S* switching off the tube voltage as soon as the mean temperature of the oil exceeds a certain limit.

The shield of an X-ray tube immersed in oil is always fitted with an expansion chamber, for instance in the form of bellows, which allows for thermal expansion of the oil without any appreciable increase of pressure. In view of the higher temperature reached by the oil, for the "Rotalix" O-55 the bellows had to be made relatively much larger. The space for the bellows was easily found in the shield at the cathode end of the tube (*fig. 5*); the cathode half of the tube is always shorter than the anode half, but for the sake of good manoeuvrability it is nevertheless desirable to make the shield symmetrical, with the X-ray focus exactly in the centre.

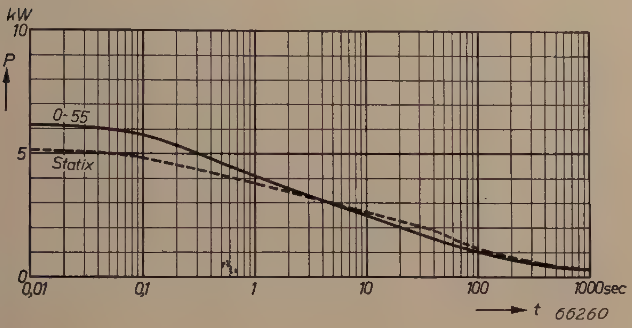

Fig. 6. Permissible load P (in kW) of the "Rotalix" O-55, when operated with 50 c/s alternating voltage, as a function of the time t in sec. Dotted curve: loading capacity of a comparable X-ray tube with stationary anode ("Statix"). As the graph shows, both tubes can be about equally loaded, but the (apparent) focus of the "Rotalix" O-55 is 1 mm × 1 mm as compared with that of the "Statix" measuring 3.1 mm × 3.1 mm, so that the specific loading capacity of the focal spot of the "Rotalix" is about 9 times greater.

Finally, *fig. 6* gives the loading capacity of the O-55 type of tube as a function of the exposure time (at 50 c/s). For comparison the permissible load is also given for a similar tube with stationary anode ("Statix"), the focus of which is three times as long and as wide as that of the O-55.

A new X-ray tube for contact therapy

When malignant growths are being treated with X-rays it is of the utmost importance to make sure that the healthy tissue around the tumour is not damaged, or at least no more than the healthy tissue can stand. The most favourable situation is when the tumour is on the surface of the skin, for then the X-rays do not have to pass through healthy tissues before reaching the tumour and it is only the tissue behind it that one must try to save. This is achieved to a large extent by applying the method of "contact therapy".

For contact therapy, which has already been fully described in this journal 6), soft X-rays are used, which are almost entirely absorbed in the tumour, and the focus is placed at a distance of only a few centimetres from the skin. With this short distance advantage is taken of the quadratic reduction of the intensity with the distance, since the relative differences in distance from focus to tumour and from focus to the underlying tissue are then large and the dose on the underlying tissue, even without absorption, is therefore relatively small.

One of the most important properties of the X-ray tubes designed for contact therapy is the "inherent filtration" of the tube. It is desired to use soft rays, which are for the greater part absorbed in a thin layer of tissue, but for this very reason such rays are easily absorbed before they ever leave the X-ray tube! The fact is that the rays have to pass through at least one window and usually two (or even more) windows: one in the wall of the X-ray tube proper forming part of the high-vacuum envelope, and another in the earthed metal shield round the tube. It is just the softest components of the spectrum emitted by the anode that these windows (the "inherent filter") absorb most.

This can be expressed in more exact terms. In passing through any material (filter) the X-radiation always becomes harder. As a measure for the hardness the half-value layer H is used, this being the thickness of a layer of aluminium or some other specified material which reduces the intensity of the radiation to half its original value. It may therefore be said that owing to the presence of the inherent filter the half-value layer of the useful radiation of an X-ray tube cannot be reduced below a certain limit. In the case of the X-ray tube for contact therapy described earlier in this journal 6) the minimum half-value layer, for a tube voltage of 50 kV, was $H = 0.30$ mm Al, or about 4 mm human tissue. The focus could be brought to a distance of 2 cm from the skin.

The small value of H mentioned was reached by a very unconventional design of the tube, which is represented diagrammatically in *fig. 7*. The ring-shaped filament lies between the anode and the patient, so that the effective X-ray beam passes out through this ring. On its way the beam passes through two windows, one in the cathode can — which in this tube is earthed — and one in a metal jacket placed round the tube to provide for cooling of the cathode can by means of a forced current

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6) H. A. G. Hazeu, J. M. Ledeboer and J. H. van der Tuuk, An X-ray apparatus for contact therapy, Philips Techn. Rev. 8, 8-15, 1946.

of air. The first window in the old type of tube was made of glass, 0.25 mm thick, and as protection against possible electron bombardment a thin gauze of nickel was placed in front of it (not shown in the drawing). The second window, in the jacket, was of "Philite".

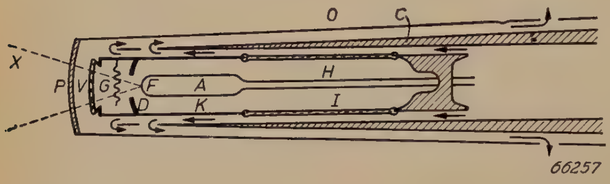

Fig. 7. Principle of the construction of the CT tube (X-ray tube for contact therapy). *K* earthed cathode can with ring-shaped filament *G* and focusing ring *D*. *A* anode with focus *F*. *I* insulation between cathode can and anode holder *H*. *V* window in the cathode can. *O* cooling jacket. *C* insulating cylinder for guiding the cooling air (see arrows). *P* window in the cooling jacket. *X* effective X-ray beam.

For most cases where contact therapy is to be applied the half-value layer of 4 mm body tissue is small enough, but for the treatment of some very superficial affections still softer rays are desired (these are often referred to as "Grenz" rays, because they lie at the "Grenz" (boundary) of the spectral range of the medically useful X-rays). For the latter cases it is necessary to try to make the inherent filter of the X-ray tube even smaller than that of the construction described.

A means of reducing the inherent filter lies in the application of what is known as **Lindemann** glass (a glass of lithium beryllium borate) as material for the tube window. This kind of glass, however, has the drawback that in course of time it disintegrates, especially in humid surroundings. Moreover it is highly fragile and — what applies to glass windows in general but especially so to windows of **Lindemann** glass — when the glass is fused into the tube wall it is inevitable that rather large differences appear in the thickness of the glass locally and as between one tube and another. The local differences cause the distribution of the dosage rate over the irradiated field of the skin to be uneven. The individual differences have to be compensated by means of separately chosen extra filters, in order to avoid too great variations in output as between one tube and another. These filters necessarily involve an undesired loss in the dosage rate.

In recent years it has been found possible to reduce the inherent filtration of the CT tube in another way. The window in the cathode can is now being made of a mica disk only about 20 microns thick, the disk being 1.5 cm in diameter and secured vacuum-tight in the opening of the cathode can by a newly developed technique [7]). When fused in, the disk remains flat and of even thickness all round, so that a uniform distribution of the dosage is obtained without any trouble, whilst the desired uniformity of all tubes does not involve any loss. This extremely thin disk of mica stands up against atmospheric pressure, but, like the glass formerly used, it cannot withstand bombardment by electrons. In the new construction it is therefore protected by a disk of **beryllium** 0.2 mm thick. This light metal, which formerly was used mainly as an alloy component in copper for contact springs and suchlike and for nuclear-physical research, has now been used in X-ray apparatus for about ten years. Owing to its very low atomic number (= 4) it is exceptionally suitable as a window for X-rays. Also the "Philite" window in the cooling jacket has been replaced by one of beryllium. In this way the minimum half-value layer of the beam of the CT tube, at 50 kV, has been reduced to 0.06 mm Al, or 0.8 mm human tissue.

The question obviously arises why the former combination of glass and nickel gauze has been replaced by mica + beryllium and not by beryllium alone. Such is in itself possible, but the solution chosen has great advantages. For the vacuum-sealing of a beryllium window the disks would have to be thicker than those which are now being used. Since beryllium is a very expensive material this makes a considerable difference in cost. Furthermore the treatment of the beryllium would then involve much more work and take longer than is the case with thin foils. Such treatment was considered undesirable, not only on account of the additional cost it entails, but more so because of the known toxic effects that beryllium has upon anyone coming too much in contact with it. Finally, the vacuum-tight fusing-on of a beryllium window is a much more difficult operation (and causes more wastage) than that of a mica disk.

The advantage of the reduction of the inherent filter of the CT tube lies particularly in the fact that even with a tube voltage of only 10 kV a reasonable dosage rate [8]) can still be obtained, namely about 6400 roentgen units per minute for 2 mA tube current and with a focus-skin distance of 2 cm. (The therapeutic total doses required are in the order of 6000 r, the permissible dosage rate is 0.3 r per week.) The half-value layer with this low voltage is only 0.3 mm human tissue! With a tube voltage of 50 kV the dosage rate at the same current and the same distance is 160,000 r/min, as against 8000 r/min in the case of the old type of tube.

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[7]) The use of mica as a window for X-rays has already been described in this journal in connection with a radiation counter tube: J. **Bleeksma**, H. J. **Di Giovanni** and G. **Kloos**, X-ray spectrometer with Geiger counter for measuring powder diffraction patterns, Philips Techn. Rev. **10**, 10, 1948. By that time J. **Bleeksma** had already initiated and developed the use of mica windows for X-ray tubes proper.

[8]) The dosage (expressed in roentgen units) is measured by the amount of energy absorbed in a certain volume of air. Since the absorption coefficient for the radiation varies greatly with the hardness of the rays there is no simple relation between the number of roentgen units per unit of time and the power entering the measuring volume. The dose per unit of time does not therefore signify an intensity of radiation (watts/cm^2), and for that reason the term "dosage rate" has been introduced; this quantity has the dimension watts/gram.

In many cases the medical practitioner will not, of course, want to work with the smallest half-value layer. For thicker tumours harder rays are needed, and the CT apparatus should therefore be able to supply also these harder rays. The window has consequently been designed as indicated in *fig. 8*. The ring carrying the beryllium window of the cooling jacket has been made so that a second ring can be screwed onto it, by means of which various additional filters can be placed in the path of the X-rays, in the form of aluminium foils. An additional filter of 0.1 mm Al increases the half-value layer from 0.3 mm tissue at 10 kV without additional filter, to 0.5 mm; at 50 kV the corresponding half-value-layers are 0.8 and 1.3 mm. Thus it is possible to vary the dosage distribution in the irradiated tissue within wide limits. For cases where a fixed irradiation technique has been established, based on the old CT apparatus, the radiation properties of the new tube can be made practically identical to those of the old one by placing in front an additional filter of "Philite" admixed with a certain quantity of metal oxide powder.

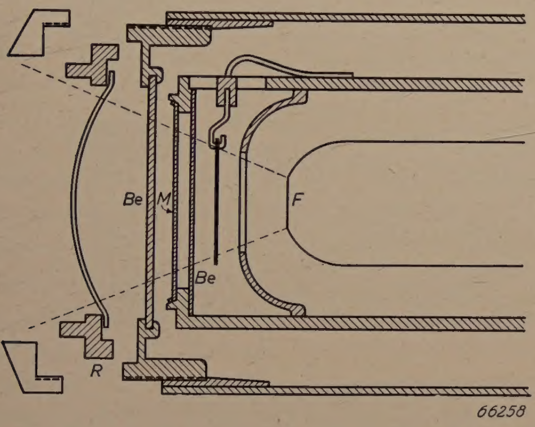

Fig. 8. New construction of the windows of the CT tube, with ring *R* for additional filters as required. *M* mica window, *Be* beryllium windows.

X-ray tube for endotherapy

It has already been pointed out that in contact therapy the conditions for a cure are more favourable than is the case with "depth therapy", where only too often nothing comes of the hoped-for success owing to the healthy tissue being seriously damaged. With some tumours **not** seated in the outer skin the advantages of contact therapy are still available to the practitioner, notably in cases of growths lying in cavities of the body, in particular the frequently occurring tumours in the uterus. For this purpose X-ray tubes have been developed with the focus at the end of a long, thin, earthed anode (immersion anode) which can be inserted in the cavity of the body, so that the source of the rays is brought in the immediate vicinity of the tumour (sometimes there may still be several centimetres of healthy tissue between the anode and the tumour). This is referred to as "endotherapy". Owing to the size and the position of the growths to be irradiated, for this application not too soft rays are desired, corresponding to tube voltages of up to say 60 kV or still better up to about 100 kV, a rather heavy filter being used.

Formerly it was quite common, and still at the present day it is a frequent practice where the situation is more favourable for it or where economic considerations dictate it, to irradiate growths in the uterus not with X-ray tubes but with radium in the form of needles or suchlike inserted *in* the tumour and left there for a few days until the desired total dosage has been administered.

It is to be pointed out that the X-ray tubes referred to here have not been developed solely with the object of replacing radium in certain cases. They make it possible for the irradiation to be carried out in a few minutes instead of days. This is of importance for a modification of "endotherapy": the irradiation of growths that may be seated deep in the body but have been made accessible from the outside by surgical operation; of course in such a case only a very short time is available for the irradiation.

For endotherapy it is particularly essential that the tube should be easy to handle, and therefore light in weight and of small size, that the anode should be very thin and of considerable length, and that the dosage rate should be high.

The endotherapy (ET) tube constructed by us fully answers these requirements. The tube with shield is illustrated in *figs 9* and *10*.

As regards easy handling, a striking advance has been made upon former designs by departing from the conventional mounting in air and placing the glass tube in oil in a sealed jacket. The principle of this construction has been followed for a long time in other X-ray tubes and in this connection has frequently been mentioned in this journal (see the foregoing, and particularly the article quoted in footnote 4)), so that we need not go into it any further here. In passing we would, however, point out another constructional feature helping to make the tube easier to handle: the cathode of the tube is connected to the high tension by means of a rubber cable with a conical end fitting into a female plug of synthetic resin attached to the tube (fig. 10). This simple plug construction, which for a considerable time has been applied by C. H. F. Müller A.G. of Hamburg for all sorts of X-ray tubes, makes it possible for the shield, for a given voltage, to be made much shorter than when applying the former combination of male and female plugs, both of synthetic resin. As a result of these expedients the total weight of the endotherapy tube with shield, which for the best design was formerly about 25 kg, has now been reduced to 3.5 kg, whilst the tube can be used with voltages up to 100 kV.

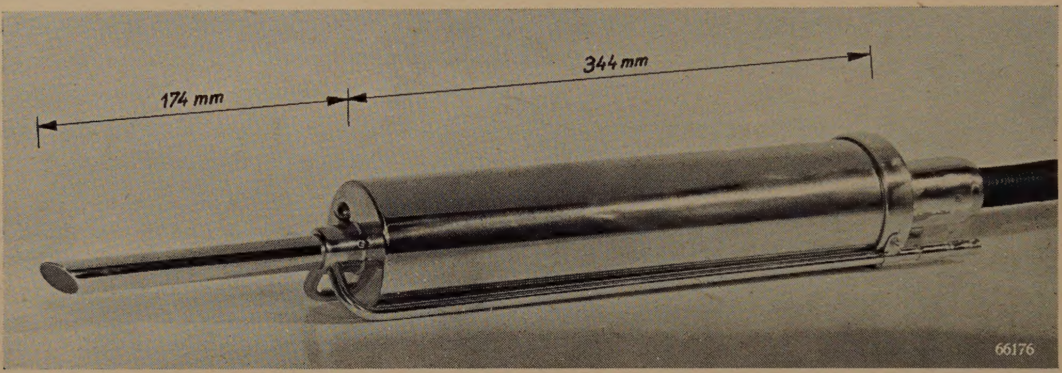

Fig. 9. ET tube (X-ray tube for endotherapy). The focus is on the oblique target at the end of the earthed anode pipe protruding from the left-hand end of the cylindrical shield. On the right the high tension cable which is connected to the cathode and the connections for the cooling water.

The other requirements mentioned, viz. a long and thin immersion anode and high dosage rate, call for rather more attention. The beam of electrons directed upon the focus must not be allowed to touch the walls of the hollow anode pipe, which means to say that it must already be extremely narrow at the entrance to the anode and must not diverge too much as it passes through. Consequently the longer and the thinner the pipe the more attention has to be paid to the problem of focusing the electron beam.

In our case it was definitely decided that the focusing would have to be done electrostatically, that is to say by giving the electrodes a suitable shape, and not by means of magnetic fields, since in the latter case there is the inconvenience that a variation of the tube voltage involves a change in the dimensions of the focus.

Electrostatically focused, narrow electron beams have already been known for some time, in their application for cathode-ray tubes where the focusing is brought about with the aid of auxiliary electrodes placed between cathode and anode and to which suitable voltages are applied, if necessary variable from the outside. For an X-ray tube, where we have to do with much higher voltages, such a method is not practicable. Here the focusing has to be brought about by a suitable shaping of the cathode, the filament mounted in it and the anode. Roughly speaking, the object is achieved with the aid of a beaker-shaped cathode with its open end facing the hollow anode and with the filament coil mounted near the bottom of the beaker. The quality of the beam depends greatly, however, upon the details of this geometrical configuration, as for instance the depth of the cathode beaker.

To make the anode as thin and as long as possible we took advantage of extensive investigations in regard to the shaping of the electrodes carried out by A. Kuntke (of C. H. F. Müller A.G., Hamburg), the results of which have been successfully applied also for various other kinds of X-ray tubes with a similar anode. With the aid of a model of the electrode configuration made to scale and immersed in a tank filled with an electrolyte, measurements were taken to determine the potential field [9]). *Fig. 11* shows as an example the field found for one of the configurations investigated. The part of the field lying between the heavily drawn equipotential line (2%) and the entrance to the anode can be regarded as a certain type of electronic lens the focusing action of which upon any electron beams entering it can be determined by geometric-optical methods. Since the directions of incidence of the rays entering this lens could not be constructed from the equipotential lines with sufficient accuracy, they were determined by imitating the narrow first part of the field by a rubber membrane and the electrons by small balls which are caused to roll over the membrane from the point where the filament would be situated [10]). From this mechanical analogue it immediately becomes evident that the spiralized filament in particular has to be constructed and mounted with a high degree of precision.

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[9]) For a further description of this method see, e.g., G. Hepp, Measurements of potential by means of the electrolytic tank. Philips Techn. Rev. 4, 223-230, 1939.

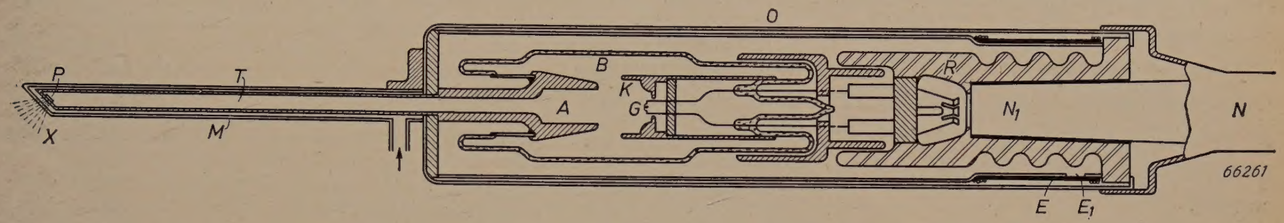

Fig. 10. Cross section of the ET tube with shield. *B* evacuated tube, *A* hollow immersion anode with pipe *T* and target *P* upon which the electrons impinge. The X-rays, *X*, pass out through the target. *K* cathode beaker with filament *G*; *R* female plug, connected to the cathode, which is mounted, together with the tube, in the shield *O* filled with oil. *N* high-tension cable with conical end N_1. *M* cooling-water jacket for cooling the immersion anode. *E* rubber tubing allowing for thermal expansion of the oil, via the opening E_1.

The focusing reached with the configuration ultimately chosen as the result of these investigations is such that with a total length of pipe of about 210 mm the diameter of the focus can be less than 6 mm. With the cooling-water jacket placed round the anode pipe we thus arrived at an overall diameter of 18 mm, which is considerably smaller than that of former constructions.

It goes without saying that the power of 400 watts previously mentioned cannot be dissipated on the focus inside the patient's body without adequate means of carrying off the heat. Hence the water cooling referred to above. The system of supply and discharge of the water is clearly shown in fig. 9. The water flows along the anode in a narrow jacket and along the target affixed at an angle to the end of the anode, this target being bombarded by the electron beam (fig. 10). The X-rays have to penetrate through the target (hence the name transmission target) and in order to avoid too great a loss of radiation by absorption the target is made of a very thin foil of copper. Copper is chosen for its good mechanical properties and its relatively low atomic number. For a good yield of X-rays in the focus, however, a high atomic number is needed and therefore an extremely thin layer of gold has been applied to the target on the inside. The flat head of the cooling jacket, through which the X-rays have to pass, consists of a very thin foil of copper, which makes the jacket watertight, whilst its outer face is covered with a thin plate of a special kind of synthetic resin absorbing the soft components of the secondary radiation by the

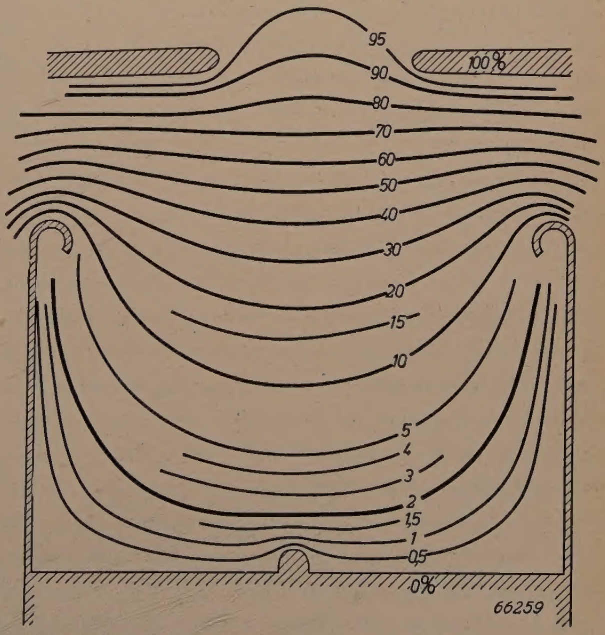

Fig. 11. Equipotential lines of the electrostatic field between cathode and anode, for the configuration of these electrodes as drawn. The lines have been constructed from measurements taken with a model in a tank filled with an electrolyte. 0% is the cathode potential, 100% the anode potential.

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[10]) See P. H. J. A. Kleynen, The motion of an electron in two-dimensional electrostatic fields, Philips Techn. Rev. 2, 338-345, 1937.

X-rays in the copper. These soft components — mainly the CuK-alpha radiation with a wavelength of about 1.5 Å — are undesired because when irradiating a tumour slightly below the inner wall of the cavity in the body they give a high extra dosage rate on that wall.

Owing to this construction of the target and the cooling jacket the inherent filtration of the tube, compared with similar tubes of a different construction, is very small, whilst the dosage rate is high. With the maximum current of 6.5 mA at a focus distance of 5 cm (in air) and a tension of 60 kV the dosage rate is 230 r/min, whilst with 4 mA and 100 kV it is 550 r/min; the half-value layers of the radiation are then respectively $H = 0.12$ and 0.24 mm copper.

Summary. Characteristic details of three newly developed types of X-ray tubes are described. The "Rotalix" 0-55 is a diagnostic tube with rotating anode especially constructed for self-rectified operation. Owing to its high loading capacity with small focus dimensions (about 6 kW during 1/10 sec on a focus of 1 mm × 1 mm) it is possible to obtain with a modest apparatus much better radiographs than hitherto. The new tube for contact therapy (CT tube) is provided with a window construction consisting of a vacuum-tight fused-in mica disk with a foil of beryllium in front of it. This gives the tube such a small inherent filtration that the minimum half-value layer of the radiation is thereby reduced to 0.3 mm human tissue for a tube voltage of 10 kV (dosage rate at 2 cm focus-skin distance 6400 r/min) and to 0.8 mm for 50 kV (160,000 r/min). The ET tube, developed for radiating tumours in or near body cavities (endotherapy) has the focus at the end of a thin, earthed, immersion anode which can be inserted in the cavity of the body. An efficient electrostatic focusing system has made it possible to reduce the diameter of the anode pipe (including the cooling jacket) to 18 mm, the total length of pipe being about 210 mm.. The input power is 400 W and the inherent filtration is relatively small, so that for 100 kV at a focus distance of 5 cm a dosage rate of 550 r/min is obtained (half-value layer 0.24 mm copper). The tube with shield weighs only 3.5 kg.